Hindawi Publishing Corporation
Advances in Meteorology
Volume 2014, Article ID 137803, 6 pages
http://dx.doi.org/10.1155/2014/137803

Research Article

Crop Yield and Temperature Changes in North China during 601–900 AD

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Received 24 April 2014; Revised 6 June 2014; Accepted 22 June 2014; Published 24 July 2014

Academic Editor: Richard Anyah

Depending on the descriptions of crop yield and social response to crop failure/harvest from Chinese historical documents, we classified the crop yield of North China during 601–900 AD into six categories and quantified each category to be the crop yield grades. We found that the regional mean crop yield had a significant ($P < 0.01$) negative trend at the rate of −0.24% per decade. The interannual, multiple-decadal, and century-scale variability accounted for ~47%, ~30%, and ~20% of the total variations of crop yield, respectively. The interannual variability was significantly ($P < 0.05$) persistent across the entire period. The multiple-decadal variability was more dominant after 750 AD than that before 750 AD, while the century-scale variability was more dominant before 750 AD than that after 750 AD. The variations of crop yield could be partly explained by temperature changes. On one hand, the declining trend of crop yield cooccurred with the climate cooling trend from 601 to 900 AD; on the other hand, the crop yield was positively correlated with temperature changes at 30-year resolution with the correlation coefficient of 0.59 ($P < 0.1$). These findings supported that high (low) crop yield occurred in the warming (cooling) climate.

1. Introduction

Food security under the changing climate is a great challenge for the world. The impact of the climate changes on the crop yield which is the actual yield in the real environments is thereby a hot topic in the field of climate changes. At present, a serious controversy still remains on the sign of impacts of temperature changes on the crop yield. It is reported that the negative impact of global climate warming on crop yield is more common than the positive impact according to the data from the past fifty years [1]. For the entire China, halves of the contributions to the crop yield made by the climate warming were positive and the other halves were negative [2–5]. However, the studies using historical data for the past several centuries reported that climate warming is good for crop harvest while climate cooling is bad for crop harvest in the world main crop production area such as Europe [6–9] and China [10–12] in the temperate region. The current lengths of studies used to evaluate climate impacts on agriculture are too short to detect long-term trends.

The existing studies using historical records mostly focused on the past several centuries which were named by Little Ice Age (LIA). The instrumental measured data-based studies reviewed by IPCC AR5 are mostly for the present warming period [13]. The reverse climate background may be a potential factor leading to the controversy. However, due to limited historical data, we know little about the correlations between the crop yield and temperature for the historical warm period which could be comparable with the present. It might be valuable to collect the harvest data for a historical warm period comparable with the present.

The proxy data-based reconstruction demonstrates that Sui dynasty (581–618 AD) and Tang dynasty (618–907 AD) (Sui-Tang dynasties, hereafter) had a warm climate comparable with the present [14]. Within the warm climate regime, there were as well temperature variations featured by a cooling trend from the late 6th century to the 9th century. The mean temperature of the winter half-year (October to April) of 570–780 AD over Central East China was 0.23°C higher than the mean of 1951–1980 AD. Local historians had focused on the agriculture history of Sui-Tang dynasties. They found that the agriculture is flourishing in the early period and shrinking in the late period. Most of these studies attributed the crop harvest to good governance, such as reducing corvée and taxes, while the crop failure was attributed to bad social governance including the lack of human resources due to wars. A few studies have pointed out that the climate change may also explain the variations of crop yield. For instance, the collapse of Tang dynasty has been attributed to low crop yield which resulted from persisting drought [15]. However, we know little yet about the correlation between crop yield and temperature in Sui-Tang dynasties.

To address the above questions, we reconstructed the variations in crop yield covering North China over the period from 601 to 900 AD, with the purpose of evaluating the effect of climate on crop yield. This paper was designed as the flowing: Section 2 describes the historical dataset and methodology of quantifying the historical crop yield compiled from historical documents; in Section 3, we would present the results; and, finally, in Section 4, the conclusions are drawn and potential research directions would be discussed.

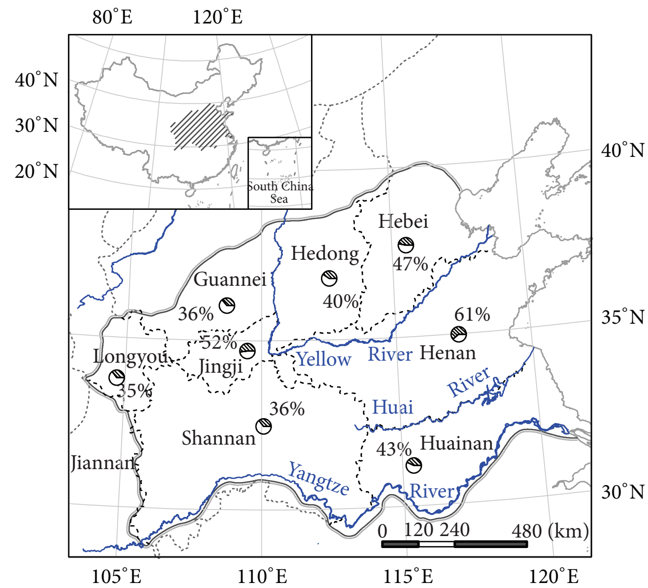

Figure 1: Study area and recorded-year fraction of each province. Shading areas in pies represent the recorded-year fraction of each province during 601–900 AD.

2. Data Sources and Method

2.1. Data Sources. Our study area is North China covering the middle and lower reach of Yellow River and Huai River reach (Figure 1). Within the study area, there were eight provinces totally in the Sui-Tang dynasties and the millet, wheat, and rice were three main crops [16–18]. The study area is also the core political area of Sui-Tang dynasties. The food production of this area plays crucial role in the security of the whole county. There are plenty of crop yield records for this area in the history documents.

We collected 468 items totally from nine historical works. The 282 items were compiled from five standard history books, which are *History of the Northern Dynasties* (“北史”) [19], the *Book of Sui* (“隋书”) [20], the *Old Book of Tang* (“旧唐书”) [21], the *New Book of Tang* (“新唐书”) [22], and *Zi zhi Tong jian* (“资治通鉴”) [23], respectively. The other 166 items were collected from *Prime Tortoise of the Record Bureau* (“册府元龟”) [24] which was the largest encyclopedia compiled during the Chinese Song dynasty (960–1279 AD). The rest 20 items were collected from *Institutional History of Tang* (“唐会要”) [25], *Commands collection of Tang* (“唐大诏令集”) [26], and *Full Tang Texts* (“全唐文”) [27].

Among 468 items, 306 items directly described both of the crop yield and famines in response to crop failure. The other 162 items only described social responses to the famines corresponding to crop failure that resulted from nature disasters and, thus, could be used as proxy data to indicate low crop yield. All of the 468 records are available for 250 years totally accounting for about 83% of the period from 601 to 900 AD. 50 years are not recorded by historical documents. These years randomly scattered from 601 to 900 AD. The durative missing records could only be found in 603–606, 656–959, and 693–695 AD. At the provincial scale, the years with available data accounted for 35%–61%, with the minimum in *Longyou Province* and the maximum in *Henan Province* (Figure 1).

2.2. Methods of Quantifying Historical Crop Yield. In Sui-Tang dynasties, the crop yield was generally quantified to be 10 grades with constant standard. Grade 10 represents the maximum yield under optimum climate conditions and best human investment. Then, grades from 9 to 1 correspond to the actual yields decreased by ~10% to ~90% to the maximum yield. The local officers usually quantified the yield with the grades of 1–10 and reported the local yield grades to the higher level of managers, such as provincial officers. Then, depending on these original quantitative records, the provincial officers would provide a qualitative assessment of crop yield of the entire province to the Empire. These assessment reports were usually saved as important archives by central government. Additionally, the historians as well wrote down the crop yield using the qualitative descriptions rather than the original quantitative records. Thus, at present, what we could obtain from historical books is usually the qualitative assessment report rather than the original quantitative records.

Depending on the descriptions from qualitative assessment report, we classify the crop yield into six categories, which are great harvest, good harvest, normal harvest, small loss, large loss, and great loss, respectively. The descriptions such as great harvest, greatly fruitful, and abundant generally indicate great harvest corresponding to grade 10 (100%). The records with good and fruitful description indicate good harvest year corresponding to grades 8–10 and are quantified to be grade 8 (80%). The descriptions such as normal, average, and no loss indicate the normal harvest corresponding to grades 7-8 and are quantified to be grade 7 (70%). The records

Table 1: The provincial crop taxes recorded in 749 AD [28].

Provinces	Jingji	Guannei	Henan	Hebei	Hedong	Huainan	Shannan	Longyou
Crop taxes (Dan*)	6688,110	8650,645	22467,641	21029,894	18544,405	5610,276	3064,740	763,868
Proportions (%)	7.70	9.96	25.88	24.22	21.36	6.46	3.53	0.88

Note. *Dan is an ancient weight unit of grain in China.

such as a little/small loss and deficient indicate the small loss corresponding to grades 6-7 and were quantified to be grade 6 (60%). The descriptions such as half harvest and famine indicate large loss corresponding to grades 3–6 and are quantified to be grade 4 (40%). The records such as no harvest, great deficient, and great famine indicate the great loss corresponding to grade no more than 3 and are quantified to be grade 3 (30%).

In addition to the abovementioned direct records, there are 162 records about the social responses to the famines corresponding to crop failure that resulted from nature disasters. According to the *Old Book of Tang* and the *New Book of Tang*, agriculture tax would be reduced by one half when the crop yield was below grade 6 and would be totally exempted when the harvest dropped to grade 3. Farmers would be free from silk and cloth tax when the harvest dropped to grade 4, as well. Thus, using these records about the social responses to the crop failure, we could also estimate the harvest grades.

2.3. Method of Estimating Regional Mean Crop Yield. Among the 468 records, there are 96 records describing the regional mean crop yield, while the other 372 records refer to the subregions of study area. We calculated the regional mean crop yield using the provincial yield with the provincial crop production weight. Such a weight represents how important the provincial production to the regional mean yield. Due to lack of original records, it is impossible to calculate the crop production weight for each province. Here, we used the fraction of provincial crop taxes to the total crop taxes of the study area to represent the provincial crop production weight. Since the tax ratio was generally even across the whole county, it is reasonable to use crop tax to represent the crop production. More crop tax indicates more crop production. As shown by Table 1 [28], *Henan*, *Hebei*, and *Hedong* provinces accounted for more than 70% of total crop tax of the study area; *Longyou* province accounted for no more than 1%. These weights suggest that the regional mean crop yield is largely determined by *Henan*, *Hebei*, and *Hedong* provinces while it is a little determined by *Longyou* province.

To calculate the annual regional mean yield, we need the annual crop yield for each province. For this study area, covering eight provinces from 601 to 900 AD, there are only 468 records. Obviously, the available records are not enough to calculate the regional mean crop yield for each year of the period 601–900 AD. According to the Chinese historian experience, because the anomalous year could impose strong impacts on human welfares, the anomalous years were rarely missing in the historical documents. In other words, the missing records year would be mostly normal years due to unextreme impact on human. Therefore, in this study, the missing record years were treated as the normal years with the harvest grade of 7 (70%).

3. Results

3.1. Annual Regional Mean Crop Yield from 601 to 900 AD. Figure 2(a) shows the annual regional mean crop yield from 601 to 900 AD. There was a negative trend at the rate of −0.24% per decade ($P < 0.01$). The wavelet analysis after removing the negative trend (Figure 2(b)) illustrates that the variations of crop yield grades had an obvious change around the 750 AD. Therefore, the whole period could be divided into two sections. Before 750 AD, the crop yield with the mean of 70.7% is obviously higher than the mean of 68.1% of the period 601–900 AD. During 601–750 AD, there were 43 years with good harvest and great harvest, accounting for 74.1% of the total good harvest and great harvest years of the period 601–900 AD. The 13 of 15 great harvest years from 601 to 900 AD occurred in 601–750 AD. During 601–750 AD, there were 13 years of large loss and great loss, accounting for 37.1% of the total large loss and great loss years of the period 601–900 AD. After 750 AD, the mean crop yield of 65.5% is much lower than the mean of 70.7% of the period 601–750 AD. During 751–900 AD, there were only 15 years of good harvest and great harvest and there were as much as 22 years of large loss and great loss years, accounting for 62.9% of the total large loss and great loss years of the period 601–900 AD.

Except for the descending trend, the crop yield also had large interannual, multidecadal (30–50 years), and century (80–100 years) variability. As shown by Figure 2, the interannual variability was significant at confidence level of 95% for the entire period 601–900 AD. The interannual variability accounted for ~47% of the total variation of yield from 601 to 900 AD. At the interannual scale, the largest increase of 46.4% (from 30% to 76.4%) occurred from 616 to 617 AD and the largest loss of 50% (from 100% to 50% and from 80% to 30%) occurred from 725 to 726 AD and from 793 to 794 AD. The multidecadal variability and century-scale variability did not persist across the entire period from 601 to 900 AD. The multidecadal variability was more dominant and persistent after 750 AD than that before 750 AD. The amplitude of multidecadal variation accounted for ~30% of the total variations from 601 to 900 AD. The century-scale variability was more dominant and persistent before 750 AD than that after 750 AD. The amplitude of century-scale variation was ~4.9% accounting for ~20% of the total variations from 601 to 900 AD.

3.2. Correlations between Crop Yield and Temperature Changes. To understand the variation of crop yield, we

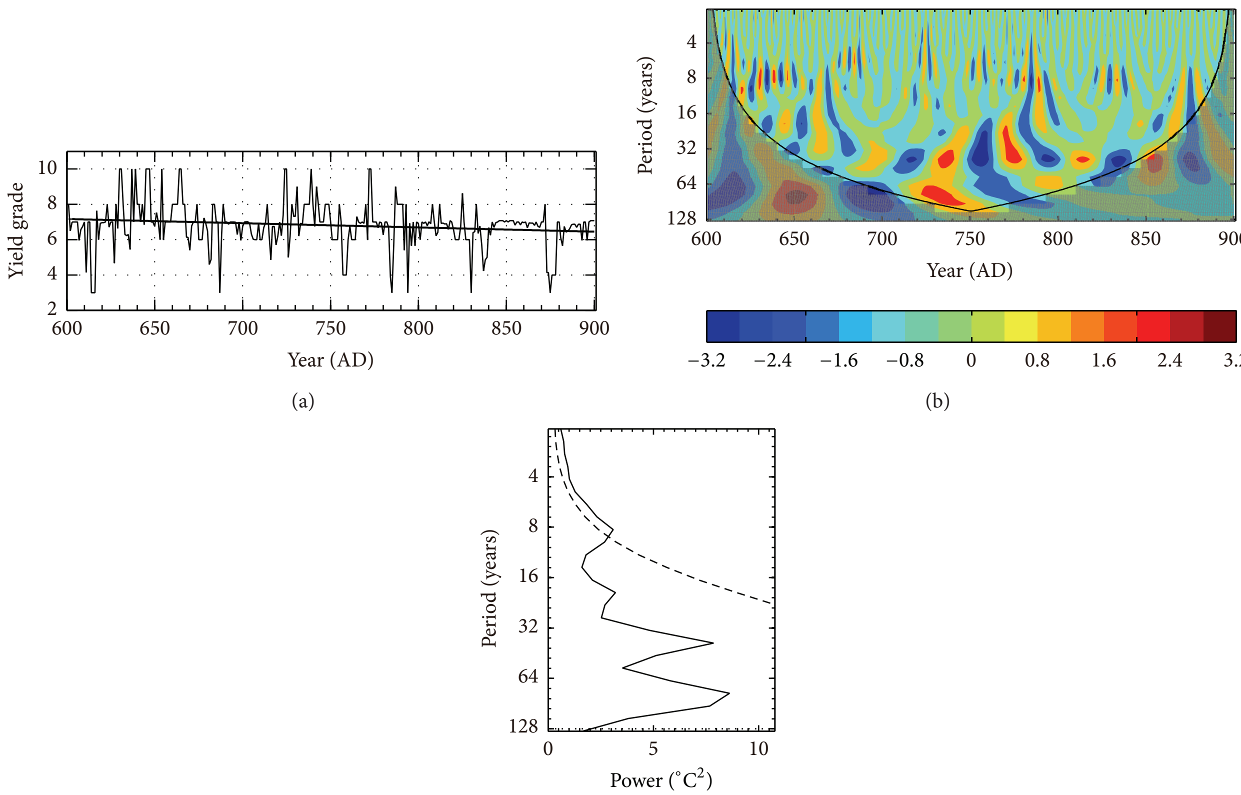

Figure 2: (a) Annual crop yield of North China from 601 to 900 AD (The straight line represents the negative trend of crop yield) and (b) real part-time frequency distribution of Morlet wavelet transform (shading denotes insignificance at confidence level of 95%) and (c) global power spectrum (dashed line denotes threshold value at confidence level of 95%).

analyzed the correlations between the crop yield and temperature changes since heat is a primary factor partly determining crop yield. The local temperature change was reconstructed using the historical phenology records through a calibration function regressing temperature anomaly to phenology anomaly [29]. The reconstructed temperature changes illustrated that there was a cooling trend at rate of ~0.33°C per century ($P < 0.01$) from 601 to 900 AD (Figure 3). It is suggested that the abovementioned descending trend of crop yield occurred under the background of climate cooling. This finding demonstrates that on the multicentury scale the crop yield was consistent with the temperature changes. High crop yield coexisted with the warm climate and low crop yield coexisted with the cooling climate.

Except for the consistent multicentury trends, the crop yield is also significantly correlated with temperature at multidecadal scale. Figure 4 illustrates the positive correlations between the crop yield and local temperature with the resolution of 30 years. The correlation coefficient of original data was 0.59 ($P < 0.1$). Actually, due to existence of long-term trend, such correlation coefficient of original data includes the contribution of the abovementioned consistent multicentury trend. To merely illustrate the correlation between crop yield and temperature variations at multidecadal scale, we removed the long-term trend of crop yield and temperature, respectively, by minusing the linearly fitting values from original data. A positive correlation of 0.44 ($P < 0.02$) between the two variations was found when the multicentury

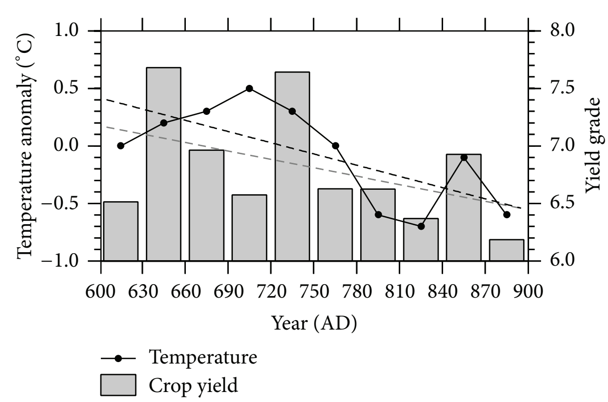

Figure 3: Reconstructed temperature series for 601–900 AD (referred to the mean of 1951–1980 AD) covering Central East China [20] and regional mean crop yield for each of the 30 years of the study area (black-dashed line and gray-dashed line denote linear trend of temperature and crop yield, resp.).

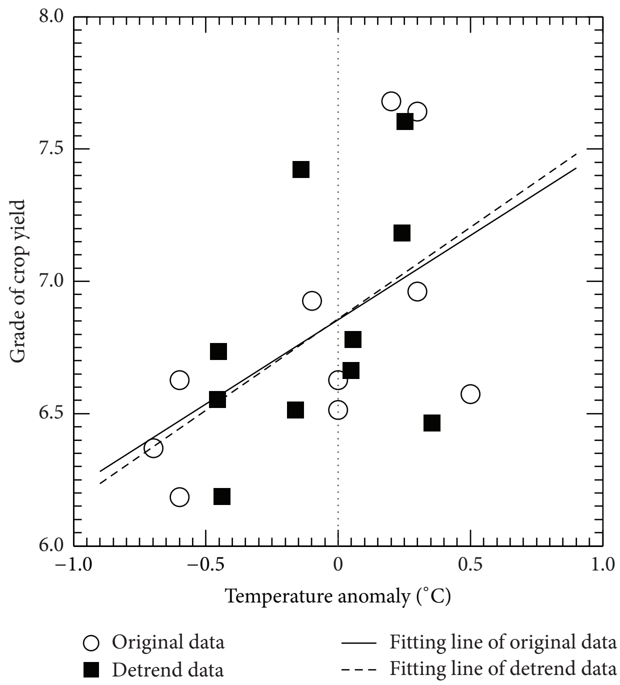

Figure 4: The correlation between crop yield and temperature.

trends were excluded. Such positive correlation confirms the abovementioned findings to the point that high crop yields were obtained generally at warm climate years. It is estimated that crop yield increased by 6.9% per 1°C warming which was slightly less than the estimation of 7.5% grades per 1°C warming from Su et al. [12].

4. Conclusion and Discussion

These observations demonstrate that from 601 to 900 AD the regional mean crop yield had a significant ($P < 0.01$) negative trend with the rate of −0.24% per decade. Except for the linear descending trend, there were also dominant and persistent interannual and multiple-decadal variability accounting for ~47% and ~30% of the total variations of crop yield from 601 to 900 AD. The variations of crop yield were positively correlated with temperature variations. The temperature could explain ~34% of variations of crop yield with the resolution of 30 years. High (low) crop yield occurred generally under the warming (cooling) climate background.

As we know, the warm climate implicates more heat resource. The site-based study demonstrates that observed warm climate is good for net accumulated production at mid- and high latitude [30]. The abovementioned positive correlation hence could be reasonable. This study demonstrates that the frequent great and good harvests in the prophase of Tang dynasty (618–750 AD) may also be supported by the warm climate, except for the developed agriculture practices and excellent governance often mentioned by local historians [31, 32].

This study highlights the importance of warm climate on the crop harvest at multidecadal and longer scales, using essential history documental records. The finding supported the existing related studies for the Little Ice Age (e.g., [8, 9, 11]). The controversy between historical studies and present data-based studies still remains, but it might be reasonable. The present climate warming is mostly attributed to human-induced CO_2 and dominantly represented as night warming [13]. The night warming enhances respiration and, thus, is not good for nutrient accumulation [33, 34]. To the historical times, we know little about the day and night temperature changes. If historical temperature variations were represented as day warming and enlarged diurnal difference, the climate warming would be good for nutrient accumulation and high yield. So, to address the controversy, more work is needed on the historical climate.

Additionally, because crop yield is determined jointly by many factors, it would be needed to perform more analyses to fully understand the crop yield variations. For instance, it is needed to analyze the role of precipitation. However, at present, the available precipitation series covering the study area for Sui-Tang dynasties [35] was reconstructed mainly using history drought/flood records. In the absence of direct drought/flood records, this construction utilized records of crop yield grades as the accessorial proxy indicators. Therefore, the reconstructed series of drought-wet index was not exactly independent from those of crop yield, and we did not analyze the correlation between them. Besides, the analyses of human management and agricultural technology are also needed to comprehensively understand the crop yield variations.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This research is funded by the "Strategic Priority Research Program" of the Chinese Academy of Sciences (no. XDA05080101), the China Global Change Research Program (no. 2010CB950100), and the Basic Research Project of the Ministry of Science and Technology of of China (no. 2011FY120300).

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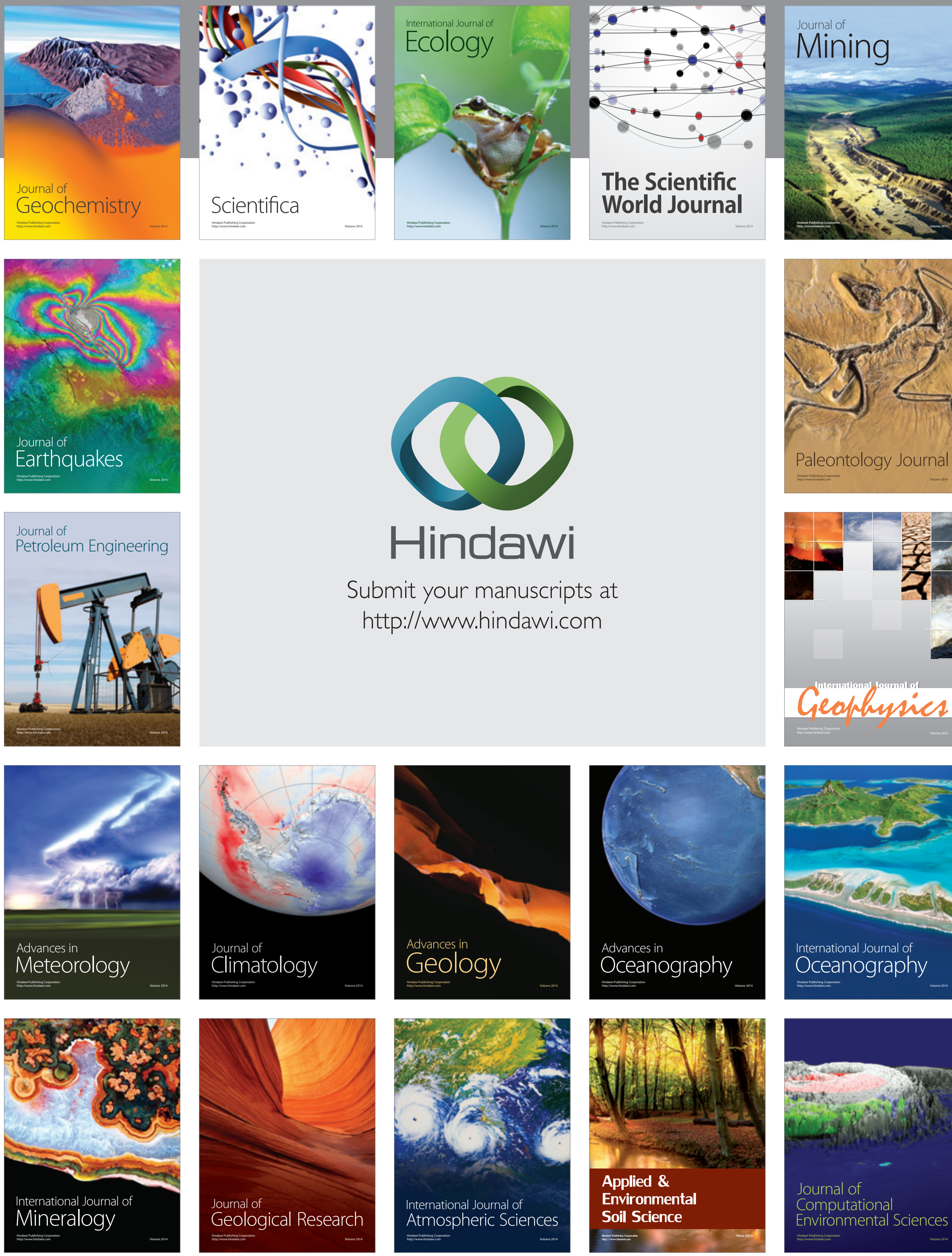
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