LETTER

Volcanic eruptions, successive poor harvests and social resilience over southwest China during the 18–19th century

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Abstract
Volcanic eruptions, climate changes and their influences on crop harvests and social development are of increasing concern in science communities. Using a dataset of crop harvest scores of southwest China from 1730 to 1910, which was derived from the memorials to the emperors in the Qing Dynasty of China, reconstructed climate proxies and the chronology of large volcanic eruptions occurring between 10°S and 15°N, we analysed possible relationships between crop harvests, climate changes and volcanic eruptions. In addition, some archives of policies and measures related to crops and social development extracted from the chronicles were used to analyse social resilience when faced with poor harvests. The results show that crop harvests in the study area generally increased with fluctuations when there were less low-latitude large volcanic eruptions from 1730 to 1810. However, from 1811 to 1910, volcanoes at low latitudes erupted more frequently, which contributed to concurrent low temperature and drought. Meanwhile, the crop harvests showed a step-down decrease during the following periods of 1810s, 1850s, 1870s and 1890s. Though, the local social system was certainly resilient in facing of such climate and agriculture disasters, i.e. the local society remained stable without significant famine, large-scale migration or social unrest until 1911. The strong resilience of local social systems owed largely to various relieving measures, such as, building barns, exempting or reducing local taxes, allocating farmland to immigrants, and central government dominated grain purchasing and distribution to alleviate disasters.

1. Introduction

As one of the most important natural disasters that humans suffer from, volcanic eruptions not only have significant climatic effects, but also disrupt the normal development of agriculture and other industries. Studies have shown that after a volcanic eruption, increased aerosol in the stratosphere prevents the earth’s surface from receiving solar radiation, as a result, the evaporation from the earth’s surface is reduced which causes water content in the atmosphere decreased (Iles and Hegerl 2015), and eventually, causes the reductions of precipitation, e.g. in Sahara and Asian monsoon regions (Anchukaitis et al 2010, Haywood et al 2013, Iles and Hegerl 2014, Shi et al 2014). The large volcanic eruptions can also be a trigger of frequent occurrence of extreme weather, such as the severe flooding in Czech Republic after the eruption of Laki Volcano in 1783, and in the early 1784, there was a rare 28-day continuous frost in Hampshire, England and other areas (Brázdil et al 2016).

Historically, the temperature drops caused by volcanic eruptions had a number of knock-on effects, such as reduction of productivity in vegetation and crops (Proctor et al 2018), famines, wars and threats to states and regimes. After the eruption of Tambora Volcano in 1815, Europe experienced severe chilling damage. From 1816 to 1818, Central Europe had a bad crop harvest and saw increased crop price, which caused a famine (Luterbacher and Pfister 2015, Brázdil et al 2016); in 1816, potato yields in Switzerland reduced by 20%–50% (Flückiger et al 2017); tens of thousands of people from the Britain and Ireland
eled to the United States to escape the famine, which made the labour market of Philadelphia filled with migrant workers in 1817 and 1818 (Luterbacher and Pfister 2015). Study (Crowley 2000) has found that the contribution of volcanic eruptions to decadal-scale changes in surface temperature rose from 22%–23% over the entire preanthropogenic to 41%–49% during the Little Ice Age (1400–1850), as a result, the temperature drops. As the contribution ratio of volcanic eruptions to climate changes increases, the impact of volcanic eruptions on agriculture is becoming increasingly conspicuous. For example, stratospheric aerosols increased by 30%–50% in the first year after the eruption of Pinatubo Volcano (Volcanic Explosivity Index \(\text{VEI} = 6\)) in 1991, a mass of volcanic ashes were erupted into the stratosphere, which contributed to the surface temperature to drop by approximately 0.5 °C. Furthermore, the spring flowering of crops in high latitudes of the northern hemisphere delayed in 1992 and 1993 (Hansen et al. 1992, Mccormick et al. 1995).

Volcanic eruptions have significant impacts on the climate over southwest China. For example, the temperature derived from the tree-ring of Gaoligong Mountain in Yunnan Province decreased within two years and dropped significantly in the second year (Li and Shao 2016) after the tropical volcanic eruptions. Historical documents also recorded similar cooling and disasters, e.g. low temperature, snow disaster, drought disaster and famine in Yunnan from 1815 to 1816 (Li et al. 2017, Gao et al. 2017). The average temperature in August 1816 at the provincial capital, Kunming City, was 2.5 °C–3 °C lower than the average temperature during 1971–2000, and there was crop failure induced famine across a large area. In Yunnan Province, victims ate soil, and starving and dying people lay on streets everywhere, and people sold their children or abandoned infants in the wild (Yang et al. 2005, Liu 2006).

Limited by the time coverage of available data, previous studies on the impact of volcanic eruptions on agriculture only focus on single events, thus it is difficult to determine its degree of influence and stability over a longer time scale. In the Mid-late Qing Dynasty (1730–1910), the Chinese historical literature, such as local gazettes, memos to emperors, recorded year-by-year continuous crop yields including harvest and failure in 83 regions, which provided data basis for studying the abovementioned issue over southwest China. In addition, Chinese historical documents recorded abundant information related to social resilience, the ways in which climate and environmental stress has impacted on social, economic, political and cultural systems and the illustration of the outcomes of these impacts. Thus, we studied the impact of volcanic eruptions on crop yields in southwest China during the 18–19th century by analyzing temperature and hydrological changes, and discussed social resilience after poor harvests. The study not only provides a historical reference and lesson for possible future agricultural disasters due to extreme weather and climate, but also offers a reference for making social resilience measures in the case of agricultural disasters under the context of frequent volcanic eruptions.

2. Study area and data

2.1. Study area

Southwest China is located in the joint area of Eastern Asian monsoon and Qinghai-Tibetan cold region, and it is rich with varied terrains from highland to plain, such as Sichuan Basin, Chuaxi Plateau, Yunnan-Guizhou Plateau, and Hengduan mountains (figure 1). It is a broad transition zone between the ISM (Indian summer monsoon) and WNPSM (western North Pacific summer monsoon) (Wang and Lin 2002). Thus the volcanic eruptions in lower and middle latitudes regions (e.g. Southeast Asia, South Asia) could very likely influence the local climate conditions both directly and indirectly. Due to its special geographic location and complicated atmospheric circulation system, southwest China is an ecologically vulnerable region, and its crop production is sensitive to climate changes (Fan 2010, Zhong et al. 2011, Duan et al. 2015). Moreover, previous study has shown that temperature decreased by 0.4–1.6 °C following the VEI ≥ 4 tropical volcanic eruptions (Sun et al 2019), because the intensified southern trough generated low vortex over the Bay of Bengal to Tibet and induced temperature drop over this region. Meanwhile, according to a millennial simulation with the FGOALS-gl climate system model, the precipitation in eastern Asian monsoon generally decreased in the first summer after large volcanic eruptions (Man and Zhou 2014, Meng, 2019).

2.2. Data sources and methods

The data used in this study include the crop harvest chronology in southwest China between 1730–1910, the climate and harvest conditions recorded in the historical documents, and the chronology of global large volcanic eruptions.

The crop harvest data were derived from agricultural archives that recorded the crop yields of the Qing Dynasty in the memos to emperors (kept in the First Historical Archives of China in the Forbidden City). The content of reports generally consisted of two parts: the overall situation of summer and autumn harvests in a whole province and some major prefectures (states), the yield scores of the governed prefectures (states) and counties. Most reports have a yield score list of each prefecture and counties as is shown in figure 2. In these reports, crop yields were generally assessed by the ‘2–10 fen’ (fen is Chinese agricultural assessment unit to measure the percentage of crops getting harvests, usually ten fen means 100% and two fen means 20%) or ‘2–10 cheng’ (Chinese unit, same
with fen)” assessment system, and some reports went to details of ‘li (approximately 0.1 fen). ‘10 fen’ or ‘10 cheng’ represents a bumper harvest, while the worst harvest was denoted by ‘2 fen’ or ‘2 cheng’ (table 1).

Referring to the administrative divisions of the Qing Dynasty, scholars have divided the major agricultural regions in Qing Dynasty into 87 sites, and each site represented 1–3 prefecture(s)/state(s) (approximately 20 counties) (Zhang 1996), which is equivalent to 1–3 prefectural level city(ies) of modern administrative divisions. The data recording format adopted 9 grades from 2 to 10, which corresponded to the autumn harvest (mainly rice and maize) conditions (table 1). Scores were usually shown in the memos together with descriptions which provided corresponding explanations. The higher the score, the better the harvest was, and vice versa. Zhang (1996) extracted the crop harvest score records, and developed harvest series for 87 sites. Out of these 87 sites, we selected 15 sites located in southwest China (figure 1), calculated the mean value to represent the harvest condition from 1730 to 1910, in order to study the possible impacts of the low-latitude large volcanic eruptions on crop harvests and climate in southwest China.

Descriptions of climate and agricultural harvest condition are available from local gazettes, a kind of Chinese historical documents. There are more than 38,000 volumes for Qing dynasty. They recorded information about nature, historical evolutions, major events, social impacts, and physical geography of each county, and they were usually compiled by official scholars at the time (Ge et al 2008). The purpose of these gazettes was not only to record the facts, but also to enable policy makers to draw a lesson from the history. Thus, the social resilience measures recorded in these archives were studied in our research.

Figure 1. Map of erupted volcanoes from 1730 to 1910 between 10°S and 15°N, and study area. (a) Distribution of volcanoes with different level of VEI, and SWC indicates Southwest China; (b) Study area and sites with crop yield distribution; different colours indicate different elevations.
Figure 2. Example of agricultural harvest reports of the southwest region in the Qing Dynasty. (Source: The First Historical Archives of China in the Forbidden City). Meaning of the Chinese words from right to left: Governor general of Guizhou Province, Yuan Chencheng reported on the fourth day of the fifth month in the 13th year of Yongzheng. The yield of winter and spring wheat was listed below. At Tongren, the region municipality directly under the Tongren Prefecture reaped an 8 fen yield, same as the yield score in Chiefian governed by Tongren Prefecture; Yongcong County was 8 fen; Jinping County was 8 fen; Kaitai County was 8 fen; The region municipality directly under the Dahing Prefecture reaped an 8 fen yield; Yield score of Weining was 8 fen; Pingyuan was 8 fen; Qianxi was 8 fen; Bijie was 9 fen.

Table 1. Assessment criteria of yield scores.

| Score | Description of crop harvests in historical documents |
|-------|------------------------------------------------------|
| 10    | Reaping a bumper harvest that was so great that the farmers had a celebration of that; This rich harvest only occurred once for 10 years. |
| 9     | A bumper year with a better harvest |
| 8     | Good harvest |
| 7     | Crops yields were at an average level |
| 6     | Crop yields were slightly lower than the average |
| 5     | Wheat and paddy rice only reaped a half and the harvest decreased, and paddy rice in summer and autumn suffered disasters. |
| 4     | Famine and disaster occurred, and loss of harvest |
| 3     | Crops withered and there was no hope to reap a harvest. |
| 2     | Barren occurred over a thousand farmland and it was hopeless to reap. There was no autumn harvest and no wheat, and crops had no harvests. |

For the chronology of large volcanic eruptions, we adopted data from the Global Volcanism Programme of the Smithsonian Institute in the United States (https://volcano.si.edu/). There were 30 low-latitude large volcanic events with volcanic explosively index (hereafter, VEI) ≥ 4 recorded during 1730–1910 (figure 1(a) and table 2).

3. Results from the data analysis

3.1. Crop harvest changes

The interannual and interdecadal variations of harvest in southwest China averaged from 15 sites and low-latitude large volcanic eruptions events since 1730 are shown in figure 3. The harvests between 1730–1810 ranged from 7.1 to 9.5 fen and showed a slight increasing trend with stable fluctuations. The mean value was 8.58 fen. But there is an exception for 1778 at 6.6 fen due to an extreme drought. As recorded in the local gazettes, Zunyi Fu Zhi, summer 1778 suffered from an extreme drought, as a result, bamboo all died from lack of water and rice price went up so high. In the autumn of that year, farmers had to dig the bitter lotus root to eat. Similar descriptions could be found in the Chongqing Fu Zhi: Sichuan suffered from a great famine, and people had to sell their children to make a living. Generally speaking, Sichuan is a fertile land, and during the past more than 100 years it has never seen such a barren and famine season. However, after 1810, the harvests ranged between 5.3 to 8.6 fen with big fluctuations, showing a continuous and significant decreasing trend at the rate of 1.23 fen/100 years. The average harvest was 7.17 fen. After the 1810s, all average scores of any decadal crop yields did not surpass the mean score during the 1730s–1810s. The harvests fell to the lowest point during the 1890s–1900s, and the average harvest in this period of time dropped by at least 2.0 fen compared with the whole reference period. From figure 3, we can see that low-latitude large volcanic eruptions occurred frequently since 1810, with 8 times from 1730 to 1810 versus 22 times from 1811 to 1910. From 1769 to 1799, there were no volcanic eruptions at low latitudes, and autumn harvests between the 1780s–1790s reached the highest level during the study period. However, after the 1815 Tambora eruption, agricultural harvest showed a great drop from 1815 to 1817, even down to 5.3 fen in 1816. The crop harvests in southwest China had four stepped declines: 1810s, 1850s, 1870s and 1890s. Among them, 1810s (the mean harvest was reduced by 1.3 fen comparing with 1800s)
and 1850s (the mean harvest was reduced by 0.7 fen comparing with 1840s) were the two periods with a dramatic decline in crop yields. This phenomenon leads us to explore the relationship between decreased crop harvests and low-latitude volcanic eruptions.

### 3.2. Possible relationships between crop yields and volcanic eruptions

Generally, volcanic eruptions have significant climate effects, i.e. they change temperature and precipitation which in the end influence agricultural production. We studied the climate conditions recorded in the Chinese historical documents when large volcanic eruptions occurred at low latitudes after the 1800s (Zhang, 2004), and several typical cases were shown here. For example, after the Tambora volcanic eruption in 1815, there was a heavy snow at the beginning of that summer in Zunyi of Guizhou Province; and at Dayao County, Yunnan Province, there was strong wind in September and the rice fields reaped nothing. At Nanhua County, the north wind in September was so cold that people felt frozen. In the summer of 1816, severe droughts occurred in Kunming, Chuxiong, Dayao, Wuding, Yuanmou, Luquan, Tengchong, Mojiang and other counties of Yunnan Province. In mid-autumn in Yao’an County, when the grain was about to mature, a north wind suddenly blew up and the millet in the field was dead without maturity. In 1817, there was no rain from mid of June to the first day of July in Yunnan Province, which was right the time when rice was flowering. This case told us failed harvest results from bad climate condition, i.e. cold in 1815, cold and drought in 1816, and drought in 1817.

Another example, after the Fuego volcanic eruption in 1857, at Jintang County of Sichuan Province, ice covered trees in summer, and birds were frozen and fell down to the ground; at Weiyuan County, the snow was so heavy that wheat and bean sprouts in the field were frozen to death in January; at Qujing of Yunnan Province, there were frost and snow in March, and soybeans and wheats were frozen to death. In 1858, at Fushun and Jiajiang County of Sichuan Province, there was a severe drought; at Wanxian County, there was a serious drought in June; at Meishan County, there was a drought in summer, and the riverbed dried up; at Chenggong, Huize, Luliang, Chengjiang, Wenshan, Maguan, Quebei and Luxi County of Yunnan Province, there were frost and snow at the beginning of August, and crops were frozen to death, people starved to death everywhere. These evidences indicate that low temperature caused the poor harvest in 1857, while the concurrent of drought and low temperature caused the death of crops.

For the 22 low-latitude large volcanic eruptions in 19 years, there was drought after 20 eruptions and cooling phenomenon as well after 11 eruptions; the climate was humid after one eruption, the Galunggung eruption in 1822; and the climate was normal when Cosiguina volcano erupted in 1835, but there was a drought in the next year (table 3). After approximately 64% of the 22 eruptions (i.e. 14 times), crop harvests all over the region dropped, while the rest 36% eruptions showed worse yields in some parts of the region. It is worth noting that the drought in Southwest China was also driven by other forcings, except of volcanic eruptions. For example, La Nina episode in tropical Pacific and negative-phase North Atlantic Oscillation may contribute the dry condition over this region (Feng et al. 2014). In addition, some scholars considered the prevailing westerly flow and the topographic conditions in Tibetan Plateau may play an important role as in 2009–2010 (Li et al. 2011). Thus, climate dynamics for the drought causes are complicate, which need more cases and climate sensitive experiments to make a further diagnosis.
Figure 3. Autumn harvests in southwest China and a chronology of low-latitude volcanic eruptions (VEI ≥ 4); thick curve: 10-year low-pass FFT filtering; green line: trends before and after 1810.

Table 3. Climate and harvest conditions recorded from Chinese historical documents at times of large volcanic eruptions at low latitude since 1810.

| Volcano       | VEI | Year | Climate      | Yield over whole region compared with last year                                      |
|---------------|-----|------|--------------|-------------------------------------------------------------------------------------|
| SSV/Awu       | 4/4 | 1812 | Drought and cold | Decreasing by 0.2 F (Fen) in 1813                                                   |
| Mayon         | 4   | 1814 | Drought and cold | Decreasing by 0.47 F in 1814                                                        |
| Tambora       | 7   | 1815 | Drought and cold | Decreasing by 1.2 F in 1815, and 0.87 in 1816                                          |
| Raung         | 4   | 1817 | Drought       | Poor harvest continued                                                               |
| Galunggung    | 5   | 1822 | Humid         | Decreasing by 0.13 F in 1822                                                        |
| Kelut         | 4   | 1826 | Drought       | Zhaotong, Simao and Dali of Yunan decreased by 1.0 F in 1827                         |
| Cosiguina     | 5   | 1835 | Normal and cold | Chongqing decreased by 3.0 F in 1836                                                 |
| Agung         | 5   | 1843 | Drought       | Chongqing decreased by 2.0 F; Bijie and Xingren decreased by 1.0 F in 1843            |
| Fuego         | 4   | 1857 | Drought and cold | Decreasing by 0.33 F in 1857                                                        |
| Makan         | 4   | 1861 | Drought and cold | Decreasing by 0.47 F in 1862                                                        |
| Merapi        | 4   | 1872 | Drought       | Guanyuan of Sichuan decreased by 3.0 F in 1872                                       |
| Cotopaxi      | 4   | 1877 | Drought and cold | Guanyuan, Dali and Kunming decreased by 1.0 F in 1877                                |
| Fuego         | 4   | 1880 | Drought and cold | Decreasing by 0.33 F in 1880                                                        |
| Krakatau      | 6   | 1883 | Drought and cold | Decreasing by 0.6 F in 1883 and 0.33 in 1884                                         |
| Tungurahua    | 4   | 1886 | Drought       | Decreasing by 0.13 F in 1887                                                        |
| Mayon         | 4   | 1897 | Drought and cold | Decreasing by 0.4 F in 1898                                                         |
| Dona Juanu     | 4   | 1899 | Drought and cold | Decreasing by 0.13 F in 1899                                                         |
| SSV/Pelee Santa Maria | 4/6 | 1902 | Drought       | Wanxian, Chengdu, Kangding decreased by 1–2 Fen in 1902                             |
| Lolobau       | 4   | 1905 | Drought       | Decreasing by 1.8 F in 1905                                                          |

3.3. Climate conditions reflected by other proxy evidences

Crop yields are generally related to climate conditions. We compared the reconstructed drought and flood index and temperature series in this region with volcanic eruptions, and analysed the possible relationships among crop yields, climate changes and volcanic eruptions (figure 4). The drought and flood index was derived from the dataset of 500-year drought and flood chart (including 120 sites in China) using Chinese historical documents (CMA, 1981), and the new hydroclimatic index over southwest China was developed by averaging drought and flood index from five sites of Wanxian, Chongqing, Tongren, Bijie and Guiyang. The July-October temperature series was reconstructed using tree-ring maximum latewood density in Yunnan Province (geographic location: 26.97°N, 99.51°E), the model to be used for reconstruction explained 58% of the variance (Li et al 2017). In terms of drought and flood variations and volcanic eruptions (figure 4(a)), the climate was dry after approximately 70% low-latitude volcanic eruptions, especially from 1811–1845 when the volcanoes frequently erupted and there were 24 years of dry climate conditions. From figure 4(b), we can see the temperature from 1810 on...
showed a gradual cooling trend, low temperatures occurred from 1814–1817, and in 1826, 1835, 1843, 1857, 1873, 1877, 1883, 1902 and 1905 after low-latitude large volcanic eruptions. From the above analysis we can see that the decrease of harvest since the beginning of the 19th century is consistent with the periods of temperature drop, occurrence of droughts and low-latitude volcanic eruptions.

However, it is worth noting that changes in crop harvests and climate were influenced by complex factors, rather than only one. For example, besides climate, crop yields are also affected by governmental policies, farming technology, input of labour force, quality of seeds, etc. While climate change is driven by solar activities and low-latitude volcanic eruptions, it is also regulated by internal modes of climatic system. In this research, we only studied the possible relationship or data pattern among crop yields, climate changes and low-latitude volcanic eruptions.

4. Changes of crop harvest and social resilience

4.1. Bumper harvest before 1800
Historically, crop yields and climate conditions had a close relationship with social stability (Cook et al 2010, Zheng et al 2014, Wei et al 2015). Between 1730 and 1799, there were few low-latitude large volcanic eruptions, and the crop harvests in the 1780s–1790s reached highest level during the 18–19th century. At that time, the government of the Qing Dynasty was in a powerful and prosperous stage. The government attached great importance to food security and disaster prevention, and implemented a series of financial policies to alleviate the burden of people to improve society’s adaptability to natural disasters. For example, policies of ‘tax exemption was accessible to new-added population’ and ‘putting capitation tax into land tax’ during the reign of Kangxi (1662–1722) and Yongzheng (1723–1735). In 1726, the policy of ‘putting capitation tax into land tax’ was implemented in Yunnan Province, and capitation was included in autumn grain to levy; as a result, 1534 taels of silver were exempted in Fumin County, Yunnan Province in 1730 (Fumin County Annals Codification Committee 1999) (tael: an ancient Chinese weighing currency unit, mainly applicable to gold and silver). Several measures, such as reclaiming new farmland, distributing land previously taken from landlord to peasants and allocating farmland to immigrants, were taken to increase the area of farmland possessed by peasants and further to improve the grain yield and lighten the burden of peasants. After the failure of Wu Sangui Rebellion, the government gave his manor to local people and submitted its authority to nearby states and counties (Yunnan Province District Annals Codification Committee 2002). In addition, serfs became land-holding peasants, and peasants directly paid taxes to the central government. At the same time, the Qing Dynasty distributed farmland to immigrants in Sichuan Province, and every family was given 30 mu (1 mu = 666.67 m²) of land as well. To facilitate grain reallocation among regions with different crop yields during the same period, the government of Qing Dynasty adopted the canal transportation system of Ming dynasty. These grains transported by canals were used for relieving areas with a famine. Meanwhile, the government of Qing Dynasty built barns everywhere to hoard up grains in case of disasters and famines. From provincial capital to prefecture, states and counties level, there were necessary barns set everywhere or some spare for backup. Moreover, the grain storage quantity was strictly stipulated. ‘The Ministry of Revenue in feudal China determined that for rice donated by Zhili Province (now Hebei Province), bigger-scale county can store 5000 dan (1 dan = 72.52–83.5 kg in Qing Dynasty), middle-scale county 4000 dan and little-scale county 3000 dan. Then, the order for doubling the storage was issued.’ (recorded in the ‘Food and Good Annals from History of Qing Dynasty’). Additionally, the construction of some engineering also provided a guarantee for agricultural and food distribution (Xuanwei City Municipal Committee Annals Chronicle Office 1999). Since the establishment of the Niulan River Bridge from Dongchuan City to Zhao-tong City, ‘the price of grain decreased steadily and common people had abundant food’ at Zhaotong City, Yunnan Province (Zhaotong City Annals Codification Committee 2000). Thus, stable grain harvests stabilized economies, and military supplies were sufficient; the government was able to take large-scale military actions.

4.2. Relief measures from 1800 to 1820
However, in the early 19th century, especially from the 1800s—1810s, low-latitude large volcanic eruptions occurred frequently, which were accompanied by drop of crop harvests and famine (Liu 2006). The decrease in grain supply caused the government of Qing Dynasty to stop its large-scale military activities in southwest China, and the expansion of the regime also stopped. It was noteworthy before the eruption of Tambora, along with three low-latitude volcanic eruptions (VEI = 4), there had been records of chilling damage in the growth season in 1813 and 1814 over southwest China (table 3).

Although after the eruption of the Tambora volcano, the harvest failed in the Yun-Gui Plateau, there was no political turmoil with the exception of the Gaoluoyi Uprising in Yunnan, the reason of which might be the long-term government policies beneficial to agricultural development and the government regulations in terms of the disaster conditions during the war and famine period as well. At the border of Yunnan, land tax was often exempted or postponed (Simao County Annals Codification Committee 1993). For some regions in Yunnan Province, the
government also set down some local regulations to keep the grain price fair and stable, such as designating rice price and punishing some illegal speculator (recorded in the ‘Food and Good Annals from History of Qing Dynasty’). In 1816, the levy time of grains owed by common people in Tengyue State, Yunnan Province, was postponed (recorded in the ‘Record of the Qing Dynasty, 1796–1820’—the records of Qing Dynasty written by some ministers at that time). During the period of disasters, for newly reclaimed farmland, the land tax was exempted. For the land tax at the beginning years of reclaiming, “people living at dependent state (local minorities distributed with land and property), paid 30%–40% tax at most and 10%–20% at least. The reclaimed farmland was exempted taxes at first, but should be taxed after three years (recorded in the ‘Food and Good Annals from History of Qing Dynasty’). Purchasing grains from other regions was also a method to relieve disaster situations for places suffering from disaster (Zhao-tong City Annals Codification Committee 2000). Another method was planting crops that were more suitable for local climate (Lijiang Prefecture Annals Codification Committee 2000). In 1818, corn was more likely to have a good harvest at the Yun-Gui Plateau, thus corns became the local staple food (Xuanwei City Municipal Committee Annals Chronicle Office 1999).

4.3. Deterioration and resilience of the social system from 1820 to 1910

During the 91 years from 1820 to 1910, drought occurred frequently in the Yun-Gui Plateau, southwest China. The drought disasters in Yunnan Province lasted as long as 40 years, with more serious years in 1849, 1876–1878, 1884, 1885, 1893, 1899–1903 and 1910, there were more than 10 county-level regions that had a drought record. There were 21 years recorded with low-temperature disasters, with severe ones in 1848, 1893 and 1895, when the records of ‘two continuous years of famine without reaped grains and the price of grains was extremely high’ were documented in the historical archives (Zhang 2004, Yang et al 2005, Luo 2006). For example, Krakatau (VEI = 6) erupted in August 1883, as a result, Sichuan and Guizhou Province experienced severe droughts in 1884 and 1885.

In 1856, a large peasant uprising led by Du Wenxiu broke out in Yunnan Province, and more than half of the province was affected by war by the time it came to an end in 1872. From 1897 to 1905, bad harvests occurred in southwest China, consequentially provincial treasuries were empty, and the contradictions between the government and common people were too deep to reconcile. Drought and famine occurred frequently in southwest China after low-latitude large volcanic eruptions in the early 1900s (3 low-latitude large volcanic events in 1902, including Santa Maria with VEI = 6). In 1910, the movement of protecting railways broke out in Sichuan, and the government of Rong County declared its independence from the Qing Dynasty. Next year in 1911, Guizhou Province, Yunnan Province and Chengdu city of Sichuan Province all announced their independence (recorded in the ‘Xuantong Biography from History of Qing Dynasty’).

In addition, there may be other reasons for the continued decline of crop harvests in the late Qing Dynasty. There was a smaller population in the 18th century, and natural fertile farmland could meet food demand; but population increased in the 19th
century, although more barren wasteland has been reclaimed, in these remote provinces such as Yunnan, ‘there are more mountains than cultivated land. All paddy fields have been reclaimed, and only hills and riverside had uncultivated lands. However, these lands were infertile so that one or two years’ rest were necessary for farming’ (Cui 2001). The barren land cultivated by people had poor fertility, and the harvest was not as good as that of natural arable land.

Though the local social system was still certainly resilient to many natural hazard impacts as evidenced in former years, the long-time close-door and self-seclusion policy, and the first and second Opium Wars (1840–1842 and 1856–1860, respectively) deteriorated the whole social-economical situations of the late Qing Dynasty. The failure of the Qing government’s internal and diplomatic strategies and lack of flexibility to responding the disasters led to a sharp decline of its state power. This meanwhile led to a significant decline in society’s ability (resilience) to respond to natural disasters, which in turn has exacerbated the turmoil of the social system after major hazard events.

5. Conclusions

Large volcanic eruption induced climate change, and further affected on agriculture. The crop harvest was relatively stable before 1810, with an average score of 8.58 fen, except that the crop yield at 1778 dropped to 6.6 fen due to an extreme drought. The harvest from 1780 to 1800 reached the highest level during 1730–1910 when no low-latitude large volcanic eruptions occurred at low altitudes. However, the crop yield in southwest China showed a continuous decline trend from 1810 to 1910, at the rate of 1.81 fen/100 years in autumn harvests. During this period, low-latitude large volcanic eruptions occurred frequently at low latitudes and up to 22 times, approximately once every five years.

Meanwhile, the crop yield in southwest China experienced four step-down declines: 1810s, 1850s, 1870s and 1890s. Among them, 1810s and 1850s were the two periods with a dramatic decline in crop yield. In the 4 years from 1814 to 1817, three large volcanic eruptions, Mayon (1814), Tambora (1815) and Raung (1817), occurred at low latitudes, and the crop yield decreased to the lowest level of the period 1730 to 1910. In the 1890s–1900s, crop yields in southwest China dropped to the lowest level at interdecadal scale. By comparing crop harvests, climate changes and volcanic eruptions, significant pattern can be found, i.e. when volcanic eruptions occurred frequently, temperatures dropped, and drought disasters occurred.

It is worthy noting that the local-scale social systems were certainly resilient to decreased crop harvests for years in that deteriorating climate conditions. The central and local governments of the Qing Dynasty implemented many disaster-handing policies and measures, such as adjusting national tax systems, land-redistribution, reallocating grains, and offering financial assistance coped with poor harvests caused by climate disasters, which eventually and positively supported the affected social and economic systems to recover soon. These measures and their effectiveness might be referable to decision makers in facing of potential poor agriculture productions in present and future. However, the failure of the general socio-economic development would lead to a general decline of the state power, which will thus erode the society’s resilience to respond to natural disasters.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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