Solar radiation, rice prices, and migration in northeastern Japan during the 18th and 19th centuries

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ABSTRACT This study explores the impact of variations in solar radiation on historical migration patterns through economic stress, such as severe famines, crop failures, and rice price fluctuations. Using individual-level panel data from annual population registers (Ninbetsu-Aratame-Cho) covering the years 1708 to 1870 CE for three agricultural villages and one commercially active town in central Fukushima, northeastern Japan, we analyzed demographic indicators – total migration, legal migration, absconding, and mortality – recorded in the registers in relation to crop failures, rice prices, and reconstructed solar radiation. Monthly solar radiation reconstructed from historical weather records indicated significant reductions during the severe famines of the 1780s and the 1830s, periods associated with increased migration and absconding. A detailed analysis of the Tenpō famine (1833–1838) demonstrated clear correlations between reduced solar radiation and subsequent sharp increases in rice prices, elevated mortality rates in subsequent years, and, with a lag of approximately two years, increased absconding. This study highlights the importance of integrating solar radiation into migration research, further advancing our understanding of the historical linkages between climate variation and human mobility.

KEY WORDS Fukushima – population – famines – migration – solar radiation – historical diaries – weather descriptions – early modern era of Japan

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1. Introduction

Analysis of historical cases provides insights into the societal consequences of climate change and informs future resilience strategies. However, previous studies have addressed extreme weather events, famines, and population decline without clearly identifying their causal relationships. Although adverse weather has been mentioned as a factor in some famine studies, the relationship between weather and social responses remains an area of ongoing investigation. In response, the pioneering study by Kurosu and Dong (2025) highlights the importance of quantitatively analyzing the links between external stresses (large-scale famines and rice price fluctuations) and individual-level out-migration, using micro-level data from northeastern Japan. However, this analysis treats famine as a binary variable (occurring or not), whereas the interplay among natural environments, social contexts, and demographic changes is far more complex. Previous research has confirmed that cold summers significantly reduced harvest outcomes during the early modern period (Hamano 2001). For instance, a cool summer likely affects harvest volumes in late autumn and elevates year-end rice prices, implying that its effects on people's daily lives are often manifested in the following year. Therefore, it is necessary to closely examine specific climate indicators (e.g., monthly solar radiation) and the degrees of poor crop yields that underlie famine outbreaks to better understand these multifaceted processes.

Nishimori and Yokozawa (2001) used multiple regression analysis based on data from 1979 to 1994 to demonstrate that rice yields in Japan are particularly sensitive to air temperature in the northeastern region and to solar radiation in the western region. They also found that years with significantly positive principal component scores for solar radiation were associated with cooler overall conditions and reduced rice yields due to lower temperatures in the northeast and decreased solar radiation in the west. These findings underscore the need to consider both the spatial and temporal dimensions of the climate to understand its impact on agriculture. Our study area was located near the climatic transition zone between regions where rice yields are more sensitive to temperature and those where solar radiation is the dominant factor. Thus, it provides a suitable setting for analyzing the historical effects of climate variations on agriculture and local populations.

Historical weather records have previously been used to reconstruct climate variations in Japan for specific seasons (e.g., summer or winter). However, few studies have attempted to estimate monthly or daily climate parameters across all seasons and locations using proxy data, such as diaries, tree rings, or lake sediment cores. To better understand the impacts of seasonal climate variation, recent studies have suggested that data at higher temporal resolutions, rather than conventional annual averages, are required. Ichino et al. (2001, 2018, 2025) proposed a method to estimate the monthly solar radiation from daily weather records (such as fine, cloudy, and rainy) documented in historical diaries. This method can estimate climatic conditions, such as low solar radiation during the summer, which are important for rice cultivation and difficult to reconstruct using other historical reconstruction methods. Rice harvesting occurred in late autumn (October–November) in northeastern Japan. This requires consideration of monthly solar radiation data from July to October, including the months immediately preceding the harvest. Thus, this solar radiation estimation method is effective for detailed analysis of rice yield fluctuations, associated price changes, and subsequent population movements.

Migration behavior was shaped by household- and individual-level characteristics and responded differently to sudden shocks compared to regular economic fluctuations (Tsuya, Kurosu 2010). Historical demographic research has shown how famine crises differ from ordinary economic fluctuations (Dyson, O'Gráda 2002) and how micro-level responses to hardship vary by social and household contexts (Bengtsson, Bengtsson, Campbell, Lee. 2004; Allen, Bengtsson, Dribe, eds. 2005; Kurosu, Bengtsson, Cambell, eds. 2010). Recent studies have also linked climatic anomalies to famine migration in Europe, including 19th-century southwest German migration to North America (Glaser, Himmelsbach, Bösmeier. 2017) and Irish famine migration of 1740–1741 (Engler et al. 2013). Our study builds on these insights, using individual-level population registers from northeastern Japan to examine migration responses to acute economic and environmental stress. During the Edo period (1603–1868 CE), several significant famines, such as Tenmei and Tenpō, had severe impacts on society. The precise dating of these famines varies across encyclopedias and scholarly studies, depending on whether the focus is on crop failure years, mortality crises, or broader social effects. For the purposes of this study, we define the Tenmei famine as 1783–1787 and the Tenpō famine as 1833–1838, reflecting periods of acute harvest failure and demographic stress in northeastern Japan (Sugano 2004; Kurosu, Dong 2025). Both famines were among the most severe crises in early modern Japan, triggered by climatic anomalies and resulting in widespread crop failures and population loss. The Tenpō famine began with prolonged cold summers and harvest failures and was further exacerbated by disease outbreaks related to malnutrition. Historical documents describe how these famines reduced local populations and prompted domain governments to enact remedial measures, such as tax reductions, recruitment of labor and marriage partners from neighboring regions, and promotion of local industries, to restore population and economic stability (Narimatsu 1985; Kikuchi 1995; Takahashi 2005).

Here, we explore the relationship between solar radiation variability, famine events, and patterns of population movement, with a focus on the Tenmei and Tenpō famines. This study differs from previous studies, which have often analyzed famine events in isolation or have not fully addressed their causal dynamics. We aim to shed light on the causal relationships among solar radiation fluctuations, agricultural outcomes, economic fluctuations, and demographic responses. Our analysis uses reconstructed monthly solar radiation derived from historical weather records, detailed population registers, and economic data such as rice prices and harvest yields.

Although general migration frameworks such as Push–Pull theory – which explains migration as the result of push factors (e.g., economic hardship) and pull factors (e.g., employment opportunities elsewhere) – have often been applied in migration research (Lee 1966; Massey et al. 1993; Das, Chowdhury 2024), the movements examined here occurred under the unique institutional and social constraints of Tokugawa Japan, where migration decisions were highly regulated by administrative permissions and collective tax responsibilities. We therefore focus on migration categories as documented in the population registers rather than applying generalized push-pull models, which may not adequately capture these historically specific dynamics. At the same time, our study adds to the growing literature on climate–migration linkages – an emerging development in migration theory – by showing how historical climatic shocks influenced migration decisions under these institutional and social constraints.

2. Study area

Fukushima Prefecture serves as a gateway between the more urbanized Kanto region and the traditionally rural Tohoku area. The Tohoku region in northeastern Japan has historically been an important area for agriculture and trade. In this study, we focused on the central region of Fukushima Prefecture, which is located in the southern part of the Tohoku region of northeastern Japan. Specifically, we investigated the town of Koriyama and three adjacent villages, Shimomoriya, Niita, and Hidenoyama, using data from historical population registers. Figure 1 illustrates the geographic distribution of these villages, and Table 1 provides their location information and the period covered.

The locations of the sites used in this study are color-coded as follows: green circles indicate diary locations (Nikko, Kawanishi, and Moriyama), orange circles indicate the communities of population registers (Koriyama, Shimomoriya, Niita, and Hidenoyama), blue circles indicate the crop data sources (Kanaizawa for harvest data and Aizu Wakamatsu for rice prices), and purple circles indicate the Japan Meteorological Agency (JMA) observatories (Yamagata, Fukushima, and Utsunomiya). The smaller inset highlights the study region in northeastern Japan. The data used comes from following sources: Historical weather database (HWDB): http://tk2–202-10627.vs.sakura.ne.jp, JMA observations: https://www.

Table 1 – Locations of historical diaries, population, and Japan Meteorological Agency (JMA) observatories utilized in this study

Data location name	Latitude (°N)	Longitude (°E)	Recording period	Types of data
Kawanishi	38.05	140.05	1830-1889	Diary weather description
Nikko	36.75	139.75	1685-1871	Diary weather description
Moriyama	37.33	140.41	1775-1867	Diary weather description
Koriyama	37.40	140.38	1729-1870	Population
Shimomoriya	37.32	140.28	1716-1869	Population
Hidenoyama	37.30	140.42	1708-1870	Population
Niita	37.42	140.36	1720-1870	Population
Kanaizawa	37.35	139.57	1716-1863	Harvests
Aizu Wakamatsu	37.49	139.93	1716-1870	Rice prices
Yamagata	38.26	140.36	1981-2010	Meteorological data from the JMA observatory
Fukushima	37.76	140.47	1981-2010	Meteorological data from the JMA observatory
Utsunomiya	36.55	139.88	1981-2010	Meteorological data from the JMA observatory

Notes: Types of Data: Historical diaries provide weather descriptions. Although the population registers cover an extended timeframe, there are missing years where data are not available: Koriyama, 18 years; Shimomoriya, 9 years; Hidenoyama, 35 years; and Niita, 4 years. The JMA observatories serve as sources of solar radiation and Tenki-gaikyō (daily weather conditions) data during the daytime.

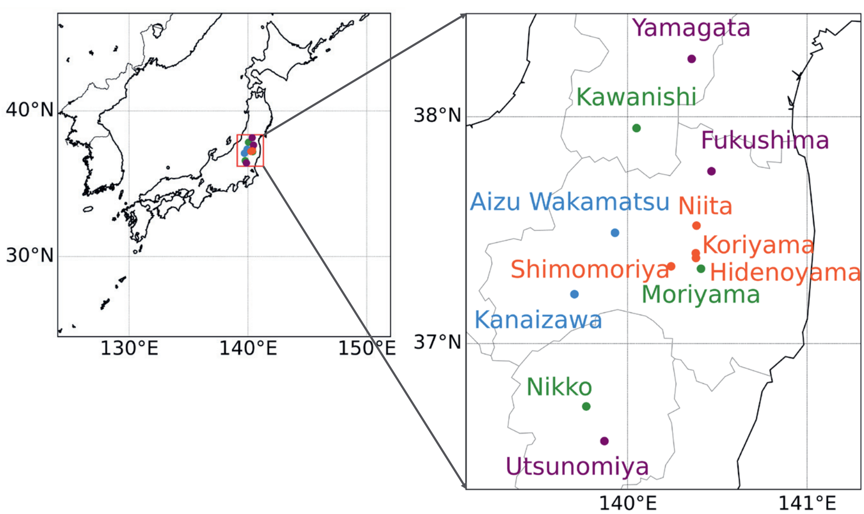

Fig. 1 – Location of the study area

data.jma.go.jp/stats/etrn/index.php, Harvest data (DANJURO database): http://www.danjuro.jp, Population data: Xavier Data, Population and Family History Project (PFHP) at Reitaku University (Kurosu, Takahashi, Dong 2021): https://www.fl.reitaku-u.ac.jp/pfhp/index-e.html.

2.1. Koriyama

Koriyama is the economic and political center of the study area. It was originally developed as a post-town along the Sendai-Matsumae route. With its increasing population and commercial sector growth, it was formally designated as a town (Machi) in 1824. Although the Tokugawa government segregated agricultural and commercial residents, Koriyama maintained both agricultural and commercial activities, embodying the characteristics of both a village and a town.

In Koriyama, many residents engage in both farming and commercial enterprises, such as operating inns while cultivating crops. According to local economic records (Koriyama-shi 1981), various businesses thrived in the town, including kimono stores, pawnshops, saké stores, and miso and soy sauce shops. Additionally, labor demands for carrying goods and prostitution were notable. Koriyama also houses the domain's offices and tax rice storehouses, and hosts periodic markets (Rokusai-ichi) six times a month, reinforcing its economic significance.

2.2. Shimomoriya

Shimomoriya is an agriculture-based village located at the foot of mountains, making it highly susceptible to climate fluctuations (Narimatsu 1985). It is particularly vulnerable to cold summers, as cold gusts from the mountains often negatively impact rice yields. Owing to these climate conditions, food shortages occasionally occur, influencing both the local economy and the population dynamics.

2.3. Niita

Niita is a fertile agricultural village with extensive rice paddies and mulberry fields. It is situated along a key transportation route connecting Koriyama and Motomiya and plays a role in regional trade and movement. However, despite its location on a busy road, Niita did not develop into a post town and remains primarily focused on agriculture (Narimatsu 1992).

2.4. Hidenoyama

Hidenoyama is one of the villages closest to Koriyama, and functions as a suburban settlement. Although rice farming remains its primary economic activity, it has a relatively more active commercial presence than other villages. However, Hidenoyama is dependent on rice farming and is supplemented with several dry crops (Takahashi 2005).

3. Data

3.1. Historical climate data

This study used two primary sources of historical weather records to reconstruct historical solar radiation.

The historical weather database (HWDB), developed by Yoshimura (2013), compiles daily weather descriptions from historical diaries. The database translated dates from the Japanese lunisolar calendar to the Gregorian calendar, covering the period of 1661–1892 CE. The sources of the HWDB include diaries from samurai households, temples, and official domain records. The recorded data describe weather conditions, such as fine, cloudy, and rainy days, as well as qualitative expressions of warmth, coldness, and wind direction. By standardizing qualitative weather descriptions through categorical values, the HWDB minimizes subjectivity in historical records. In addition, it provides visualized data in the form of weather maps and calendars, thereby improving the accuracy of climate reconstruction.

The Moriyama domain diaries contain official documents of meteorological observations recorded from 1775 to 1867 CE. These records were systematically collected by Saeko Narimatsu, organized and hosted by the Population and Family History Project (PFHP) at Reitaku University. In addition, they transcribed and digitized daily weather descriptions, including extreme events. These records were compiled into a database for paleo-weather analysis and integrated into DANJURO (Population Analysis System in the Edo Period) by Kawaguchi (2009) for open access. The diaries included daily descriptions of weather conditions, such as fine, cloudy, and rainy days, and qualitative expressions of warmth or coldness.

3.2. Observational meteorological data from the Japan Meteorological Agency

The observational meteorological data recorded by the Japana Meteorological Agency (JMA) from 1981 to 2010 were used to calculate the conversion parameters. Figure 1 and Table 1 summarize the locations of the Yamagata, Fukushima, and Utsunomiya observation sites and the temporal coverage of the datasets, respectively.

The "*Tenki-gaikyō*" (weather condition records from the JMA) from the Yamagata, Fukushima, and Utsunomiya observatories were recorded twice daily by local observatories (once during the daytime and once at night), following the method described in the Guideline for Statistics of Surface Meteorological Observations (Japan Meteorological Agency 1990). Ichino et al. (2001) described the processes, procedures, and regulations for generating *Tenki-gaikyō* in JMA. Hirano, Mikami, Zaiki (2022) also applied daytime *Tenki-gaikyō* as they were assumed to be the most similar to historical daily weather records. Daytime *Tenki-gaikyō* records were generated by summarizing cloudiness- and precipitation-related parameters recorded every 3 hours from 06:00 to 18:00 (Japan Standard Time).

Daily total solar radiation (*S*) data were sourced from JMA surface weather observations at the Yamagata, Fukushima, and Utsunomiya observatories. The period from 1981 to 2010 was selected to determine the conversion parameters for estimating solar radiation in historical reconstruction.

3.3. Demographic data

This study uses demographic, economic, and harvest data to examine socio-economic fluctuations and their impact on migration patterns in early modern Japan.

The population data used in this study were derived exclusively from the *Ninbetsu-Aratame-Cho* (population registers, NAC hereafter), a type of household register widely compiled during the Tokugawa period. NAC lists individuals' names, ages, and relationships to household heads, and includes not only kin but also non-kin members and servants. Compared to other types of household registers (*Shūmon-Aratame-Cho*), often used in historical demography in Japan, NAC typically recorded population on a de facto basis and excluded religious affiliation. The NAC records used here are copies kept by local village officials after submission to domain authorities, with annotations capturing vital events such as births, deaths, marriages, and migration, including reasons for migration (e.g., marriage, adoption, service). The Fukushima NAC registers, in particular, are considered among the most detailed and continuous sources for early modern Japan, spanning more than a century with relatively few gaps, making them highly valuable for demographic analysis (Cornell, Hayami 1986; Hayami, Kito, Tomobe, eds. 2001). Data from the NAC registers are among the most comparable historical population panel data in East Asia.

These NAC manuscripts were transcribed into Basic Data Sheets (BDS) and linked across successive years using names, ages, and household affiliations to form longitudinal life-course records (Kurosu, Takahashi, Dong 2021). The resulting individual-level database (the Xavier Database) harmonizes person-level information across annual registers. Quality control included checking for duplicate records and inconsistent age reporting across consecutive registers. Because NACs were enumerated annually (at the beginning of the third lunar month), events occurring between enumerations may be omitted, an important consideration for demographic calculations.

The NAC provides detailed information on migration timing (whether an individual out-migrated in the following year) and reasons for migration, including destinations. Individuals could migrate multiple times; for example, a person might out-migrate for service, return after completing a contract, and later leave again. Each event was counted separately. We constructed four macro-level indicators: (1) all out-migration (all exits for any reason), (2) legal migration (marriage, adoption, service, and similar cases), (3) illegal migration (absconding without permission), and (4) deaths. For analysis, population records and these events were pooled, and each indicator was calculated as the number of events per thousand population for the corresponding year; i.e., crude out-migration rates, crude legal migration rates, crude illegal migration rates, and crude death rates.

Tokugawa society imposed strict controls on movement beyond village or town boundaries. Travel required official permission, and documents were checked at transit points. Legal migration typically included marriage, adoption, service, or work. In contrast, during times of economic hardship, some individuals left without permission (absconding). Because taxes were paid collectively, villages were incentivized to prevent absconding and to actively search for missing individuals for up to 180 days. Retaining farmland and property was often more desirable than permanent relocation, even during periods of food scarcity (Kurosu, Dong 2025).

For legal migration (e.g., marriage, adoption, service), destinations were usually recorded, and such moves typically involved joining another household or employer, often within the same region. In contrast, destinations for absconding were rarely recorded, so it is unclear whether individuals moved to neighboring regions or farther away. In either case, migration – legal or illegal – removed individuals from the tax obligations of their original village or town, even though surrounding areas would also have experienced similar climatic and price shocks.

3.4. Economic data

Rice price data, compiled by Iwahashi (1981), covers the period from 1716 to 1863 CE. The rice price series is originally from the Ge-kan (Volume 2) of Wakamatsu-shi-shi (Wakamatsu-city History) published in 1941–1942, which contains a record of rice prices in the Aizu local market. While the rice price records cover 220 years (1643–1863), information on the nature of the prices is limited. Nevertheless, as they are the only available grain price series covering a long duration in the area for this period, they have been used repeatedly in studies of price history (for further discussion of the price, see Kurosu, Dong 2025). A note of caution is necessary here that rice price fluctuations were not always determined solely by market factors such as harvests and demand for consumption, trade, and storage and were often also influenced by political and policy-related decisions of the local government (Kurosu, Dong 2025). With this caution in mind, this analysis uses raw rice prices (in ryo per koku) in the Aizu market.

Harvest data were extracted from the DANJURO database (Kawaguchi 2009), including annual rice yield records from 1730–1800 for the Kanaizawa villages in Aizu County (http://shutou.danjuro.jp/ine/ine.php). The dataset included maximum, average, and minimum yield values.

4. Methodology for reconstructing solar radiation

4.1. Calculating solar radiation from weather descriptions

Qualitative weather descriptions (such as fine, cloudy, and rainy conditions) indicate the degree to which incident solar radiation is reduced by clouds and other atmospheric conditions. The target variable was total downward solar radiation at the surface. This study estimated historical solar radiation using weather descriptions from historical documents, such as diaries and observational logbooks, based on the methodology established by Ichino et al. (2001, 2018, 2025). Weather descriptions were categorized into three levels and converted into solar radiation using conversion parameters determined from modern observations (Table 2).

The method described by Ichino et al. (2001) was used in this study to derive the equation that elucidates the relationship between solar radiation and modern weather descriptions and to estimate solar radiation from modern weather descriptions. This equation is based on the relationship between modern solar radiation and *Tenki-gaikyō*. Daily total solar radiation (S) was obtained from the daily JMA surface weather observations. Normalized S is denoted as q and is calculated using Eq. (1):

$$q = S/S_{TOA} \quad (1),$$

where S_{TOA} is the daily insolation received at a horizontal surface at the top of the atmosphere, which is calculated using the equations described by Kondo and Xu (1997; Eqs. 38–40). Although it varied throughout the historical period, we consistently applied the recent value of 1.365×10^3 W/m² as the total solar irradiance (the so-called solar constant) to calculate S_{TOA} in this study.

The average ratio of q for each month to the weather level k is denoted as $q_{mean}(k)$, which was calculated at each location where *Tenki-gaikyō* and solar radiation were used (Table 1 and Figure 1). We speculated that the $q_{mean}(k)$ values for the 19th century and 1981–2010 are identical.

Table 2 – Specifications of weather levels and the classification of weather descriptions

<table>
<tr><th>Type</th><th>Category of weather description</th><th>HD</th><th>TG</th></tr>
<tr><td rowspan="9">Weather level k</td><td>Fine</td><td>1</td><td rowspan="4">1</td></tr>
<tr><td>Fine, partly cloudy</td><td rowspan="7">2</td></tr>
<tr><td>Half fine, half cloudy</td></tr>
<tr><td>Cloudy, partly fine</td></tr>
<tr><td>Cloudy / half fine, half rainy</td><td>2</td></tr>
<tr><td>Cloudy, partly rainy</td><td rowspan="4">3</td></tr>
<tr><td>Half cloudy, half rainy</td></tr>
<tr><td>Rainy, partly cloudy</td></tr>
<tr><td>Rainy / snowy</td><td>3</td></tr>
</table>

Note: HD – For weather descriptions in historical documents, TG – Weather descriptions from the Japan Meteorological Agency, Tenki-gaikyō. Source: Ichino et al. (2025).

Tenki-gaikyō was classified into three levels of Type TG, shown in Table 2. This classification system in Table 2 was derived from the nine categories of *Tenki-gaikyō* (Ichino et al. 2001). Based on our recent investigation, we adopted the three-level HD classification shown in Table 2, which was developed by comparing weather descriptions from historical diaries with *Tenki-gaikyō* and examining their characteristics. This system can resolve discrepancies in weather conditions, as indicated by similar descriptions in *Tenki-gaikyō* and historical diaries. Here, Type TG is for Tenki-gaikyō, and Type HD is for historical diaries.

Solar radiation and weather conditions are strongly correlated. Therefore, we initially explored the quantitative relationship between q and *Tenki-gaikyō*. The solar radiation values for all months were highly correlated with daily weather descriptions. Consequently, the weather levels deduced from weather descriptions were converted into solar radiation using Eq. (2):

$$S_{ej} = q_{mean}(k_j)^{*}\, S_{TOA\ j} \qquad (2),$$

where S_{ej} is the estimated solar radiation, j is the day, and k_j is the weather condition indicated by “weather level”. $S_{TOA\ j}$ is the daily solar radiation that reaches the top of the atmosphere on day j, and $q_{mean}(k_j)$ is a conversion parameter determined by weather level k_j and calculated using weather observations recorded by the JMA from 1981 to 2010.

The errors in S_{ej} compared to the observed S were insufficiently small. However, the variation was similar to that observed for S. This method uses $q_{mean}(k_j)$ corresponding to the three weather conditions for each day. Therefore, we used the monthly mean S_{ej} described by Ichino et al. (2001) to minimize ambiguity.

Historical weather descriptions were categorized into appropriate weather levels k (type HD) to estimate the historical solar radiation. As shown in Table 2, ‘fine’ was designated as weather level $k = 1$, 'rainy' as $k = 3$, and 'snowy', 'graupel', 'hail', and 'sleet' were considered equivalent to rainy ($k = 3$). As mentioned in the typical weather expressions for the categories, $k = 2$ includes other weather descriptions, unlike those in *Tenki-gaikyō*. For example, temporary clouds in historical diaries were categorized as $k = 2$, whereas weather in *Tenki-gaikyō* was classified as $k = 1$. In historical diaries, a rainy day that temporarily stops the rain is also categorized as $k = 2$; however, in the case of *Tenki-gaikyō*, it is categorized as $k = 3$.

4.2. Parameter determination with modern observations

To calculate $q_{mean}(k)$, observational data consisting of simultaneous weather descriptions (*Tenki-gaikyō*) and solar radiation measurements are required. However, historical weather observations typically do not coincide spatially with modern instrumental observation locations. Observational data at the JMA locations listed in Table 1 and Figure 1 were used to estimate and calculate the parameters. This study was based on data from the Climatic Division of Radiation provided by the Japan Weather Association (JWA). The similarities between seasonal solar radiation patterns determine these climatic divisions.

Ichino and Mikami (2003) examined the range of spatial applicability of $q_{mean}(k)$ at a location to estimate the monthly mean solar radiation using the approach described by Ichino et al. (2001), with $q_{mean}(k)$ applied to other locations. They reported that the estimation errors remained within acceptable ranges when applying $q_{mean}(k)$ within the same climatic division. Considering these results, the JMA locations used for the estimations (listed in Table 1) were selected according to the climatic divisions of solar radiation defined by the JWA.

5. Results and discussion

5.1. Climate and migration in the 18th and 19th centuries

The population trends of the three villages and Koriyama, as well as their pooled total, are depicted in Figure 2, providing a baseline for interpreting demographic shifts during the famine periods. The figure also includes the pooled total for all four communities. Since the duration of the registers for these four communities varies and also contains gaps ranging from 4 to 35 years (Table 1), we applied linear interpolation to estimate missing values. We then summed the population estimates to construct the overall trend, 1729–1869 CE.

The pooled population of the four communities exhibited an overall upward trend, increasing from 2,051 to 3,811. However, significant declines occurred

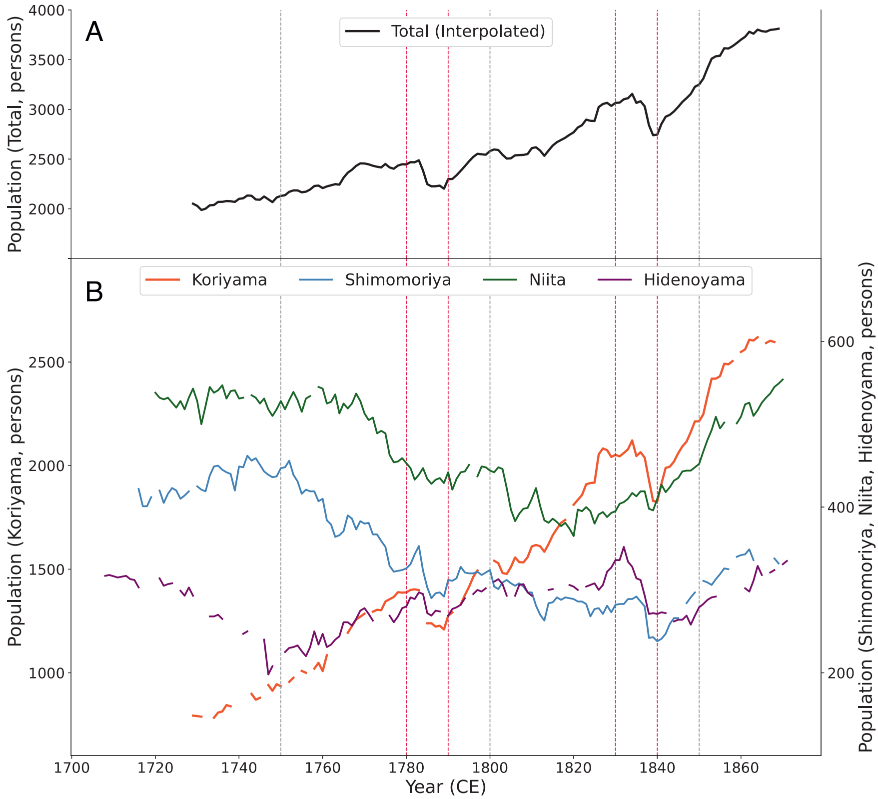

Fig. 2 – Population trends (1708–1870 CE): (A) Total population (black), and (B) populations for Koriyama (orange), Shimomoriya (blue), Niita (green), and Hidenoyama (purple). The red dashed vertical lines indicate the major famine years, including the Tenmei famine (1780s) and Tenpō famine (1830s). Source: Xavier Data, Population and Family History Project at Reitaku University.

during the Tenmei and Tenpō famines, reflecting the devastating demographic impacts of these crises. Despite these disruptions, a gradual recovery is evident in the following decades. Within this general trend, notable variations exist among the four communities. The agricultural villages of Shimomoriya and Niita began losing their population before the Tenmei famine and did not recover until the 19th century, whereas Hidenoyama showed more stability.

In contrast, Koriyama experienced consistent population growth, except during the two famines, with its population more than tripling over the observation period. While famines played a major role in shaping demographic trends, it is important to recognize that people's lives were also influenced by other factors. Following the Tenpō famine, however, all four communities exhibited a sustained upward trend, leading to population growth toward the end of the Edo period and

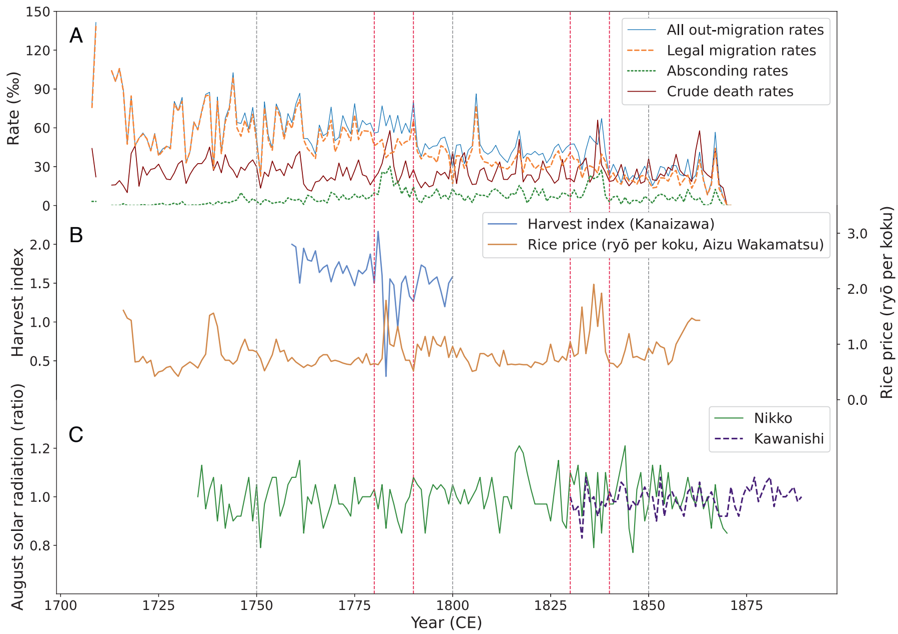

Fig. 3 – Long-term variation (1700–1870 CE) in (A) migration rates (blue, orange, and green lines; left axis), Crude death rates (dark red), (B) Harvest index (light blue line; middle axis), Rice prices (brown line; middle axis), and (C) reconstructed August solar radiation ratios (green and purple dashed lines; bottom axis) at Nikko and Kawanishi. The red dashed vertical lines indicate the major famine years, including the Tenmei famine (1780s) and Tenpō famine (1830s).
Sources: HWDB; JMA observations; DANJURO database; Xavier Data, Population and Family History Project at Reitaku University.

into the new era. While the subsequent analysis pools data from all four communities, we remain mindful of the demographic variations among them.

Figure 3 illustrates the long-term variations in migration, mortality, rice harvests, and rice prices in the study region from 1708 to 1870 CE. It also includes estimates of August solar radiation derived from weather descriptions in the diaries of Kawanishi and Nikko. The red dashed vertical lines in Figure 3 indicate the Tenmei famine (1780s) and Tenpō famine (1830s). Both the death rate and absconding rate increased during these famines, indicating that demographic conditions were significantly affected by famine-related stress. Furthermore, a strong correlation was observed between variations in August solar radiation and agricultural production. Reductions in August solar radiation appear to have led to lower rice yields and subsequent increases in market prices. In the 1830s, particularly, reduced solar radiation was closely associated with poor harvests and a rise in migration rates.

Rice prices rose sharply during the Tenmei (1780s) and Tenpō (1830s) famines. In the 1780s, this surge followed a decline in rice yields, which in turn coincided with reductions in August solar radiation. In the 1830s, although harvest data are not available, similarly low levels of solar radiation were recorded, and rice prices again rose significantly.

5.2. Solar radiation and migration during Tenpō famine

Figure 4 presents variations in reconstructed solar radiation, rice prices, and demographic indicators, including mortality and migration rates in the 1830s. The solar radiation data, covering June to September, were estimated at three locations (Nikko, Kawanishi, and Moriyama) based on weather descriptions recorded in historical diaries. The figure also includes rice prices from the Aizu Wakamatsu market and demographic data on mortality and out-migration during the Tenpō famine period.

In Moriyama, solar radiation in June was intermediate, between that observed in Kawanishi and Nikko. This pattern likely reflects the northward movement of the seasonal rain front. When the front is located farther south, solar radiation in Nikko tends to be lower. As it shifts northward, radiation in Kawanishi decreases. From July to September, Moriyama and Nikko exhibited similar radiation patterns, suggesting that Moriyama reflected Pacific-side climate characteristics, in contrast to Kawanishi on the Sea of Japan side. These differences, clearly captured in the diary-based records, demonstrate regional and seasonal differences in solar radiation during the Tenpō famine period.

Monthly solar radiation at Moriyama was notably low during the summers of 1833, 1836, and 1838. These years correspond to the Tenpō famine, which was marked by cool summers and widespread food shortages (Kikuchi 1995, Hamano 2001) and accompanied by notable demographic disruptions (Kurosu, Dong 2025). A sharp increase in rice prices was also observed during this period. A similar pattern was noted in the 1780s, when reduced solar radiation coincided with poor harvests and significant price surges (Fig. 3). Although direct harvest data are not available for the 1830s, the recurrence of low summer radiation during these years, as shown in Figure 4, suggests that a comparable sequence of agricultural and economic stress may have occurred. Mortality increased in 1834, likely reflecting the delayed effects of the exceptionally low radiation observed in the preceding summer. In 1835, the rate of absconding also increased, suggesting that some individuals left their registered communities in response to continuing economic stress. A sequence from reduced summer solar radiation to elevated mortality and increased absconding suggests that weather conditions during the growing season disrupted agricultural output and subsequently influenced demographic trends.

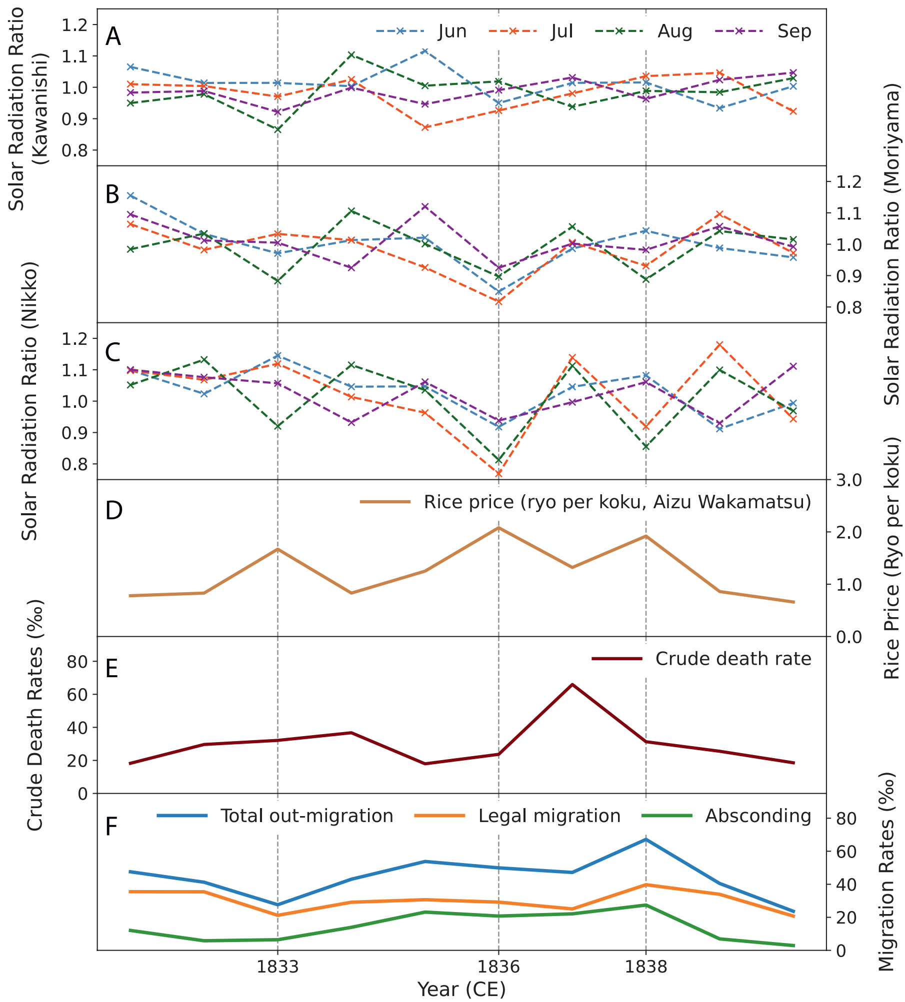

Fig. 4 – Variation of selected characteristics in the 1830s CE. A, B, C: Monthly solar radiation ratios at Kawanishi (A), Moriyama (B), and Nikko (C) in June (blue), July (orange), August (green), and September (purple) of the 1830s. D: Raw Rice prices (brown lines). E: Crude death rates (dark red line). F: Migration rates (blue dashed line = total out-migration; orange dashed line = legal migration; and green dashed line = absconding). The vertical dashed lines indicate severe famine years (1833, 1836, and 1838). Sources: Iwahashi (1981); HWDB; JMA observations; DANJURO database; Xavier Data, Population and Family History Project at Reitaku University.

Demographic indicators and rice prices exhibited different patterns in relation to climate conditions. Rice prices tended to rise in years of low solar radiation and decline in the following year. Mortality increased in the year after poor weather conditions and subsequently declined. Legal migration was observed throughout the period, with higher levels recorded in 1835 and 1838. As shown in Figure 3, both mortality and absconding increased during major famines. However, absconding was low in 1833, began to rise in 1834, and continued to increase through 1835. It remained at a high level in 1836 and 1837, followed by an increase in 1838. In 1839, the rate dropped to the same level as in 1833. The decline in absconding observed in 1839 followed the end of the famine and improvements in weather and economic conditions. While this overall trend is consistent with broader recovery, the specific factors underlying the timing and pace of this decline remain unclear. Possible explanations include prior out-migration, institutional constraints, or data limitations. The distinct temporal pattern of absconding, unlike other indicators, warrants further investigation. However, as the population registers (Ninbetsu-Aratame-Cho) have been preserved in only a limited number of regions, it is difficult to generalize these findings to other areas.

6. Conclusions and future directions

This study explored the impact of solar radiation fluctuations on agricultural production, economic conditions, and population dynamics, focusing on the Tenpō famine in 19th-century Japan. The analysis revealed a strong association between reduced solar radiation from July to September and subsequent increases in rice prices, mortality, and migration. In the years identified as famine years, solar radiation levels dropped markedly during these critical months, resulting in a sharp rise in rice prices by the end of the year. Mortality rates surged by the following March, and migration increased significantly in the year that followed, especially cases of absconding.

A key feature of this study was the use of high temporal resolution data, which enabled a more detailed reconstruction of seasonal variation in solar radiation. While previous reconstruction methods have primarily focused on early to mid-summer, this study underscores the importance of weather conditions from July to September in determining rice yields. The results indicate that decreased solar radiation during this period contributed to poor harvests, which in turn led to market fluctuations and ultimately affected demographic patterns.

Additionally, we analyzed population dynamics in northeastern Japan by combining data from a town and three surrounding villages. The results showed that mortality increased in years with reduced solar radiation, followed by a rise in absconding. This study represents an initial step toward examining the demographic consequences of short-term weather anomalies in Japan during the late 18th and early 19th centuries, using community-level historical data. Based on monthly solar radiation estimates reconstructed from historical diaries, we identified a sequence linking abnormal summer weather, poor harvests, and rising rice prices, which was followed by increased mortality and eventually higher levels of absconding. It is not yet clear whether solar radiation influenced migration directly or primarily through the effects of poor harvests and rising prices during the famine years. This approach emphasizes specific climate indicators during the growing season, instead of vague generalizations such as "adverse weather".

This study drew on a rare combination of historical diaries, rice price records, and population registers, all preserved for a single region in northeastern Japan. These sources enabled a joint examination of climate-related crop failure, economic pressure, and demographic responses during the Tenpō famine. The analysis was developed through collaboration among researchers from multiple disciplines, integrating perspectives from historical demography, economic history, and climate reconstruction. Although the scope of this study is regionally limited, the methodological approach may be extended to other areas and periods where comparable historical sources exist. Such efforts will contribute to a more comprehensive understanding of population movements under environmental and economic stress in early modern societies.

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