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Domino effect of climate change over two millennia in ancient China's Hexi Corridor

Qi Feng[1*], Linshan Yang[1*], Ravinesh C. Deo[2], Amir AghaKouchak[3], Jan F. Adamowski[4], Roger Stone[5], Zhenliang Yin[1], Wei Liu[1], Jianhua Si[1], Xiaohu Wen[1], Meng Zhu[1] and Shixiong Cao[6]

Climate change, population growth and extreme events can trigger social crises and instability. The processes that dominate a society's emergence, resilience and collapse, and the complex interactions among such processes, operating within a small region, at a multicentury or even larger time scale, remain to be identified. The causes or driving forces responsible for societal changes must be identified for a plausible explanation. Historical records provide unique examples of societies that have failed to develop buffers and strategic resilience against climate change and natural variability. Using a wide range of observations from China's Hexi Corridor, the complex interactive processes linking climate change with human society over the past two millennia were investigated. This paper proposes a domino effect resulting from a society's failure to respond to climate change in which individual small problems create a greater challenge over long time spans. Building resilience against the impacts of climate change requires a deep understanding of social and environmental feedbacks to create a reliable buffer against future changes. This study offers lessons learned from the past 2,000 years that remain relevant today, given the projected changes in climate and extreme events.

Exploring relationships between climate change and evolutionary progression of human society is a challenge that stimulates lengthy, yet healthy, debates within and between the scientific and policy-making communities[1,2]. Field data, as well as archival and reliable paleo records, offer a unique opportunity to study societies affected by climate change in different historical time periods, providing insights into the vulnerability of human society to future climate change, although most historical climatic changes appear to have been considerably less severe than the changes projected for the coming century[3,4]. Throughout history, societies around the world have been confronted by shifts in climate, altering the quantity and quality of food and water available. Scholars have persistently attempted to confirm causal relationships between climate change and massive social disturbances, including societal collapse and the rise and fall of empires and dynasties in China, Europe, Africa and many other regions, albeit on different time scales[5–8]. Efforts to explore how climate change plays a causal role in societal crises and its socioeconomic impact in the preindustrial era[9] are limited by the paucity of high-resolution paleoclimate data and historical documents[10,11].

Although a large body of literature confirms that climate is a key factor in historical human crises[12,13], the underlying causal linkages remain difficult to pinpoint[14]. So far, only one study has confirmed this preconceived causal relationship to occur on a continental scale and multidecadal time scale[5]. One example is the increasing body of research on anthropogenic climate change and its causal impacts on human society[15,16]. Likewise, historical insights and paleo records enhance our understanding of a society's vulnerabilities to past climatic changes and their implication for the future[17].

China's Hexi Corridor (Supplementary Fig. 1) provides an opportunity to examine societal changes in relation to past climate change because of its distinct combination of climate, geography, human history and wide range of ethnicities (Supplementary Fig. 2)[18–20]. As a multiethnic region, the Hexi Corridor has been a hub of both confrontation and integration of different nationalities[21,22]. This paper draws insights by reviewing evidence from long-term (AD 2–1988) climate and interrelated social data. These data were used to systematically analyse the role of climate change in historical social crises in the Hexi Corridor over the last two millennia[23]. Furthermore, the authors discuss how building societal resilience could potentially allow a society to bear the consequences of events that may be driven by climatic change.

Interactive processes linking climate change with society

Trends in social variables within the Hexi Corridor over the past two millennia, in parallel with those of temperature and precipitation, show strong and statistically significant correlations ($r > 0.79$) between temperature and key biological parameters; for example, tree-ring width and grain yield (Supplementary Table 1). Precipitation had a much weaker effect on tree-ring width ($r = 0.09$), yet showed a statistically significant relationship with grain yield ($r = 0.49$). In turn, both biological parameters were significantly associated with social variables. For example, tree-ring width showed a moderate association with both grain prices and wages ($r > 0.48$). The temperature in the Qilian Mountains was significantly correlated with precipitation ($r = 0.61$), suggesting that regional cold phases were associated with dry conditions, a combination that would decrease grain yield. This expected relationship

[1]Key Laboratory of Ecohydrology of Inland River Basin, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, China. [2]School of Sciences, Centre for Applied Climate Sciences & Centre for Sustainable Agricultural Systems, Institute for Life Sciences and the Environment, University of Southern Queensland, Springfield, Queensland, Australia. [3]Department of Civil and Environmental Engineering, and Department of Earth System Science, University of California, Irvine, CA, USA. [4]Department of Bioresource Engineering, Faculty of Agricultural & Environmental Sciences, McGill University, Montreal, Québec, Canada. [5]Centre for Applied Climate Sciences, Institute of Life Sciences and the Environment, University of Southern Queensland, Toowoomba, Queensland, Australia. [6]School of Economics, Minzu University of China, Beijing, China. *e-mail: qifeng@lzb.ac.cn; yanglsh08@lzb.ac.cn

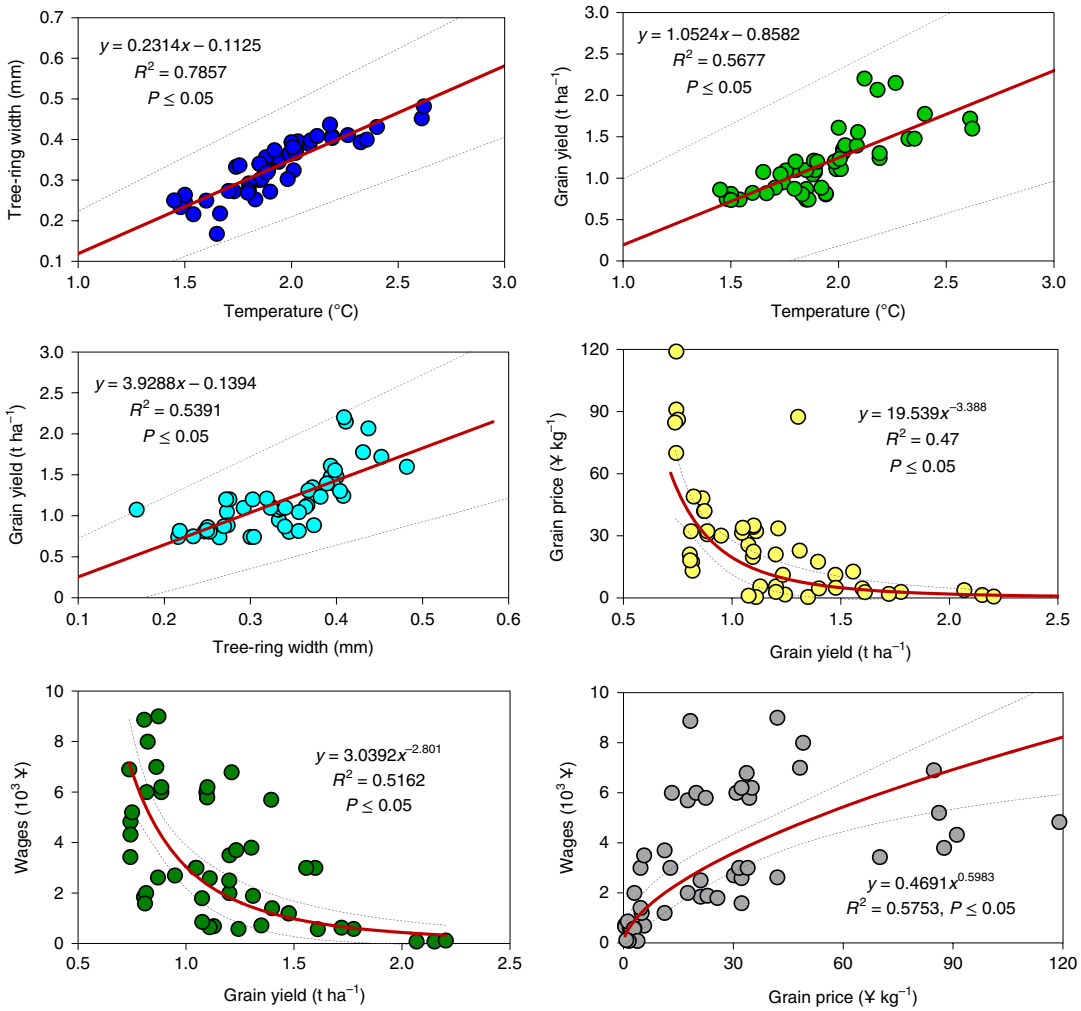

Fig. 1 | The relationship between environmental and socioeconomic variables (temperature, tree-ring width, grain yield, grain price and wages). The red lines show the regression lines/curves and the dashed lines represent the 95% confidence interval.

is supported by a significant increase in grain yield with increasing temperatures ($r=0.79$), as decreases in grain yield would result in food insecurity, leading to adverse societal impacts and instability. Indeed, the decreased grain yield was strongly and significantly associated with decreases in social stability: $r=-0.63$ for grain prices, $r=-0.56$ for wages, $r=-0.49$ for famine and $r=-0.60$ for social disturbances (Supplementary Table 2).

The relationships reported above had consequences that are historically documented. Temperature series were divided into different phases based on anomalies above or below $\pm0.2\sigma$°C (σ, s.d.). During the long-term C1 cold phase (AD 290–400, average temperature $=-0.47\sigma$°C), in the 'Five Hu' period of the Eastern Jin dynasty, famine in Mongolia led (on five occasions) to migrations of large populations of nomadic Mongols, and this led to a period of disorder (Supplementary Fig. 8a,c,j,k). These migrations became invasions, leading to warfare and eventual conquest of China by the nomads. Colder and longer than C1, the second cold phase, C2 (AD 1550–1740, average temperature $=-0.84\sigma$°C), dubbed the 'Little Ice Age' in Europe, led to a significant decrease in food production, causing famines and plagues and, secondarily, conflicts and social disturbances (Supplementary Fig. 8d,k,l). These disturbances coincided with the end of the Ming dynasty and the onset of the Qing dynasty.

The analysis revealed that both warmer and wetter periods were associated with increased grain yield, leading to a decrease in migrations and conflict. For example, the warm phase W1 (AD 830–1000, average temperature $=+1.61\sigma$°C) was associated with greatly increased grain yield, which in turn was associated with decreased migration, conflict and social disturbances (Supplementary Fig. 8a,d,j,k,l). This period coincided with the flourishing era of the Tang and Song dynasties.

Plots of environmental versus socioeconomic variables (Fig. 1) showed that biological productivity was strongly and significantly correlated with climate signals. Both tree-ring width ($R^2=0.79$) and grain yield ($R^2=0.57$) increased significantly with increasing temperature. Grain yield also increased significantly with increasing tree-ring width ($R^2=0.54$), providing additional evidence of their common response to temperature change. The socioeconomic factors were also strongly correlated with agricultural productivity. Grain prices ($R^2=0.47$) and wages ($R^2=0.52$) were significantly negatively correlated with grain yield.

The response of social crises (for example, migration, disturbance, plague, famine, conflict and human lifespan) to grain price (Fig. 2) showed that the frequency of all crisis indicators rose significantly with rising grain prices: $R^2=0.66$ for social disturbance, $R^2=0.50$ for famine, $R^2=0.55$ for migration, $R^2=0.44$ for conflict and $R^2=0.27$ for plague. These last trends may have resulted from significant increases in grain price brought on by decreasing temperatures and, thus, decreasing grain yield (Supplementary Table 2). Lifespan, which reflects the nutritional status and overall

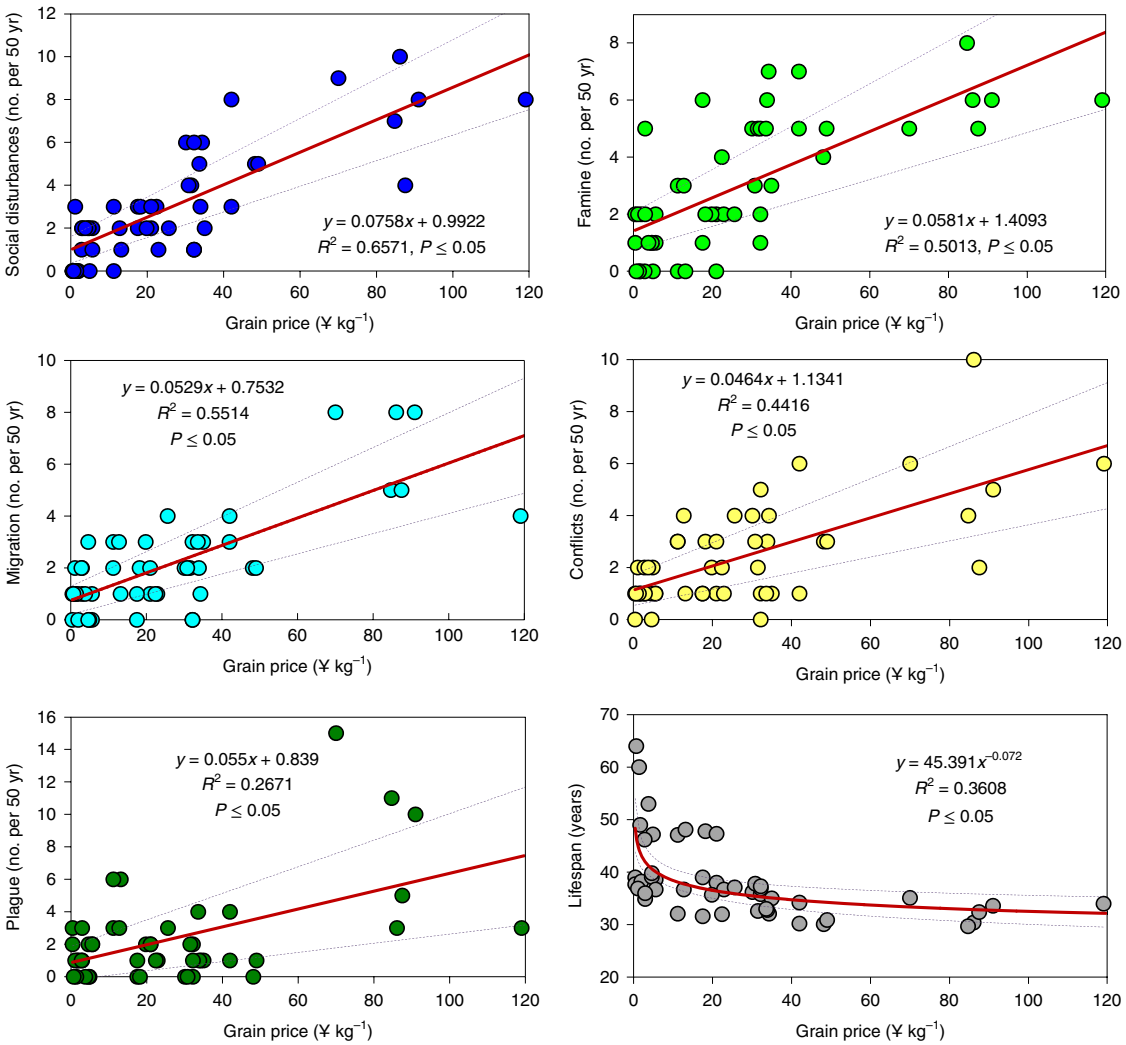

Fig. 2 | Response of indicators of social crisis (frequency of social disturbances, famine, migration, conflict and plague) to inherent changes in the price of grain and subsequent impacts on human lifespan. The red lines show the regression lines/curves and the dashed lines represent the 95% confidence interval.

societal health, decreased significantly ($R^2 = 0.36$) with increasing grain prices.

Plots of socioeconomic indicators versus the rate of incidence of social crises (Supplementary Fig. 9) generally showed significant positive correlations: social disturbances increased significantly in response to increasing famine, migration, plague and conflict. Migration increased significantly with increasing famine and conflict increased significantly with increasing migration.

The results of this study demonstrate to what extent climate change, agricultural productivity and social crises in China's Hexi Corridor have interacted over the past two millennia. Such information can set a strategic foundation to address present challenges and formulate a thriving, healthy human society. Population size and growth rate were significantly positively correlated ($r = 0.78$) and that population was significantly positively correlated with grain production ($r = 0.51$) but significantly negatively correlated with wages ($r = -0.19$) (Supplementary Table 2). This suggests that population size and growth were influenced by multiple factors (Supplementary Table 4) and that individual variables could only explain part of these complex relationships.

Despite the widespread use of data to explain social and scientific phenomena, the present authors acknowledge that statistical correlations alone do not imply causality but most of the causal relationships drawn from reliable data spanning the past two millennia appear to be logically plausible. To establish a statistical basis for this deduction, causal relationships among variables were examined by means of Granger causality analysis (see the Supplementary Information for details)[23]. The Granger causality analysis results (Supplementary Table 3) showed that the null hypothesis (no causal relationship) for most of the proposed linkages among the pertinent factors could be rejected at a 0.05 significance level. A significant ($P \leq 0.05$) causal relationship existed for 18 of the 25 tested linkages between climate change and human crises and the remaining seven linkages were marginally significant ($P \leq 0.10$).

The chains of causality outlay significant relationships among causal factors and their consequences, clarifying how climate change may have led to social crises in the Hexi Corridor. A causal relationship can only be confirmed if the cause precedes the effect and if the causal series contains relevant information that can explain and forecast the resulting series. Considering the above caveat, the following chains of relationships were identified (Fig. 3):

- Climate change → food production and supply → socioeconomic consequences
- Grain yield → grain price → lifespan, plague, famine, migration, conflict → social disturbance → social crises → population

- Famine → plague → lifespan
- Famine → migration → conflict → population

Domino effect of climate change on social stability

Temperature was significantly positively correlated with precipitation and cold periods were coupled with dry conditions. Cooler periods may have contributed to periodic decreases in agricultural production by reducing the duration of the growing season combined with a moisture deficiency that limited crop growth. Although temperature strongly affected social variables, the latter's relationship with precipitation was much weaker (Supplementary Table 2). The weak relationship between precipitation and social variables is probably because precipitation in the Hexi Corridor is extremely limited (~100 mm yr^{-1}) and the main source of water is snowpack stored in the Qilian Mountains. It was inferred that temperature was the key factor that directly affected grain yield, which in turn affected prices and the ability to afford grain. Indeed, the data used in this study also revealed that temperature change might have been the root cause of human crises in the Hexi Corridor. In snow-dominated regions, runoff is closely related to both snow water equivalent and temperature[24]. In the Hexi Corridor where agricultural water relies on snowmelt from the Qilian Mountains, a cold spell may reduce the runoff and thereby affect agricultural production[6,21,25].

Climatic perturbations are only one of many triggers that can affect natural and socioeconomic outcomes and certain preconditions are necessary before triggers stimulate a change. Preconditions include anthropogenic environmental changes arising from the overexploitation or injudicious use of resources. Accordingly, an analysis based on the richest members of society would be misleading because their greater wealth would help them survive problems, such as famine, that would otherwise kill the commoners. The cascading feedbacks that have been inferred in this research, through the use of the Granger causality analysis technique, suggest that growing social polarization may have repeatedly led to conflicts that ultimately resulted in societal disruptions. The magnitude of the resulting crisis would be contingent upon the degree of the resource depletion and the effectiveness of social buffering mechanisms.

Hexi model overlap with European model

Focusing on the effects of cooling on agricultural production, war and population decline at interannual to multidecadal scales, Zhang et al.[25] proposed a model of climate change and large-scale human crisis for the European ice age. In contrast, we describe the domino effect that can result from a society's failure to deal with climatic changes over long time spans by reviewing evidence from long records (2–1988 CE) of climate and interrelated social data, including fine-grained paleoclimate reconstructions and historical documents for a smaller region, over a longer time span. Despite the difference of temporal and spatial scales, the Hexi model in this study does have some similarities to the European model. We confirmed both that climate change has created a chain reaction on human society and, particularly, that cooling caused successive declines in biological productivity and rises in socioeconomic crises and social disturbances.

Some scholars have stated that such associations, if any, may be coincidental rather than causal linkages[12]. However, the present study goes beyond simple statistical correlations[25] or derivative compilations of historical data[14,25]; its causality analysis results are both consistent with the history of the region and physically reasonable. Although the application of well-established social theories may be able to explain isolated short-term historical crises by relying on the importance of the roles of leaders, elites and their ideologies, theoretical foundations have a notable challenge clearly explaining long-term series of recurring crises in different historical periods (particularly in periods with different stages of civilization,

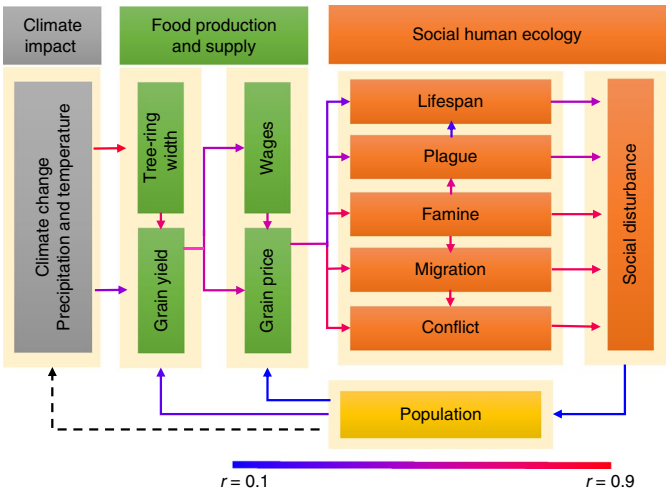

Fig. 3 | A conceptual model of the domino effect of climatic change seen in the causality sequences developed for the Hexi Corridor from AD 2 to 1988. Significant causal relationships were identified by means of the Granger causality analysis. Solid lines denote causal linkages: their colour represents the correlation coefficient, while dashed lines represent potential present-day feedbacks.

cultural integration, levels of economic development and natural resource availability), when the preceding conditions are causally related to subsequent conditions[12,14].

Bridges between climate and society and adaptation

Directly related to the consequences of climate change on food security and social stability, overpopulation remains a thorny issue. Our findings echo Malthusian theory in suggesting that, when a region's population exceeds the ability of agricultural production to sustain itself, famine is likely. This can then lead to societal crises such as starvation, premature death and, possibly, plague. While Malthus argued that rapid and unhindered population growth was the cause of human misery[26], the findings of the present research indicate that misery may instead be triggered by climate-induced agricultural decline. Malthusian theory emphasizes that increasing demand for food is the cause of instability, whereas this research found evidence that the cause was the shrinking food supply. In practice, since the problem relates to an imbalance between demand and supply, both factors have probably contributed to social instability.

Although the demand for food increases with population, it is also true that a growing population provides more agricultural workers who can produce food to offset the growing demand. If there is enough arable land and the state of agricultural technology is sufficient to increase crop yields, this can delay or prevent a food crisis. However, attempts at more intensive cultivation have not always been able to keep pace with the needs of a growing population during periods with a severe cold climate[6]. In this scenario, even if the demand needed to fulfil minimum nutritional requirements remains essentially constant, the food supply decreases, possibly below the minimum required level.

Although the dependence of preindustrial societies on agriculture is widely recognized, it should not be forgotten that even with the present abundance of food, modern industrial societies depend equally heavily on a stable food supply and that this supply can be seriously jeopardized, at least in some regions, by climate change[25]. It is necessary to identify the dynamics that stimulate societal adaptation to potential crises in order to determine whether a society is resilient. The challenge remains of how to develop a comprehensive, integrated model that convincingly explains past interactions between society and the environment

that sustained it, and that captures the broad dynamic principles that cut across all combined human–environmental systems[27]. This understanding can reveal the necessary precautions that governments and stakeholders must take to prevent a reoccurrence of past crises[28]. The climatic perturbations and environmental degradation that our research identified did not contribute to the triggering of every societal crisis; in some cases, the most prominent driver at an early stage was an institutional failure that resulted from the inability of societal institutions to address collective problems[29,30]. Given the size and complexity of modern societies, a strong governmental role will be necessary to absorb the costs associated with natural disasters, including those directly linked to climate change. On the other hand, governments cannot solve every problem. We believe that community awareness of the potential causes of instability and recognition of novel conditions will also be critical elements of effective responses[31–35].

Methods

Variables used. High-resolution climate reconstruction data including temperatures in China's Qilian Mountains as a whole and precipitation on the northeastern Tibetan Plateau, as well as historical documents that provide data on biological productivity, human socioeconomic conditions and social disturbances, were collected. Specifically, social disturbances included famines, migrations, conflicts and plagues in the Hexi Corridor. See Supplementary Notes in the Supplementary Information for details.

Verification of causal linkages between climate change and human society. Core evidence data and correlation was used to identify significant relationships between climatic information and various forms of social crisis[36]. Upon deducing a significant relationship, the Granger causality analysis was adopted as an effective method for identifying causal relationships. Multiple regressions were used to understand the feedback relationships between the underlying variables. For details, please refer to Supplementary Methods in the Supplementary Information.

Data availability

The data on climate change, biological productivity and socioeconomy that support the findings of this study are available from the corresponding author on reasonable request.

Code availability

The source codes of the Granger causality and regression analysis used in this study can be obtained from the corresponding author on reasonable request.

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Author contributions

Q.F. and L.Y. designed and performed the research. Q.F., L.Y., Z.Y., J.S., X.W., M.Z. and R.C.D. analysed the data. Q.F., L.Y., W.L., A.A., J.F.A., R.S. and S.C. wrote the paper. L.Y., R.C.D. and Z.Y. prepared the figures. All authors reviewed the manuscript and approved it for submission.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Q.F. or L.Y.

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