Journal of Cleaner Production 435 (2024) 140303

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Building smallholder-adapted climate-resilient systems: Evidence from China's apple farms

Zhiping Duan [a,1], Jinghan Li [a,c,1], Fan Li [b,d,1], Jiping Ding [e], Yuanmao Jiang [f], Jianguo Liu [g], Weifeng Zhang [a,*]

[a] State Key Laboratory of Nutrient Use and Management, College of Resources and Environmental Sciences, China Agricultural University, Beijing, 100193, China
[b] College of Economics and Management, Huazhong Agricultural University, Wuhan, 430070, China
[c] Knowledge, Technology and Innovation Group, Wageningen University and Research, Wageningen, 6706KN, Netherlands
[d] Macro Agriculture Research Institute (MARI), Huazhong Agricultural University, Wuhan, 430070, China
[e] College of Economics & Management, Northwest A&F University, Shannxi, 712100, China
[f] College of Horticultural Science and engineering, Shandong Agricultural University, Shandong, 271018, China
[g] Michigan State University, Center for Systems Integration and Sustainability, Dept Fisheries & Wildlife, E Lansing, MI, 48823, USA

ARTICLE INFO

Handling Editor: Cecilia Maria Villas Bôas de Almeida

Keywords:
Smallholder-adapted climate-resilient system
Institutional price-enhancing mechanism
Organizational production-support system
Public extension system
Cash crop production

ABSTRACT

Climate change affects crop production globally, and cash crops are particularly vulnerable, which may threaten human livelihoods. However, limited attention has been paid to building climate-resilient systems, especially for smallholders producing cash crops such as apples, which account for 13% of the global fruit consumption. In this study, we developed a smallholder-adapted climate-resilient system (SA-CRS) conceptual framework and applied this in an empirical assessment of the adaptation of smallholder apple farmers (SAFs) to the risk of low temperature during flowering (LTF) in China. The results show that average daily minimum temperatures have decreased by 1.77 °C, and the LTF hazard probability has increased by 6.1% from 1999 to 2018. Approximately 96.4% of the SAFs in the study regions reported LTF impacts in 2018, and 29.8% experienced apple yield losses averaging 16.43 t/ha. Notably, most SAFs in the Loess Plateau region with poor SA-CRS reported apple yield reduction. Such adverse effects lowered economic returns and further prevented SAFs from adopting adaptive measures, resulting in a vicious circle. By contrast, an effective SA-CRS in the Bohai Bay region has greatly reduced the risks, and a positive economic return further incentivizes the adoption of further adaptive measures, creating a virtuous circle. Our study showed that to achieve an effective SA-CRS, a market-oriented nexus approach is required that integrates an institutional price-enhancing mechanism (contributing 84% to smallholder decision-making), an organizational production-support system, and a public extension system tailored to the needs of SAFs.

1. Introduction

Climate change significantly affects agricultural production (Ray et al., 2015), with adverse effects being particularly strong among developing countries where food systems are fragile (Choquette-Levy et al., 2021). Studies have shown that climate change is causing extreme weather events (e.g., floods, droughts, and extreme heat and cold) that can reduce crop production by more than 30% (Ray et al., 2015). Long-term climate change could lead to significant annual harvest losses and agricultural shocks (Fanzo et al., 2018; Cottrell et al., 2019), with approximately 20–36% of the global population being affected by food shortages due to extreme climate events by 2050 (Hasegawa et al., 2021).

Most research has focused on climate change challenges and adaptation strategies pertaining to staple crops such as wheat, rice, and maize (Mehrabi Z, 2019; Davis et al., 2020; Moat et al., 2017), and relatively little attention has been allocated to the examination of cash crop systems. However, cash crops, the economic mainstay for smallholders in developing nations, are equally exposed to significant risks posed by climate change. A recent study found that extreme weather adversely affected apple production quantity and quality, resulting in revenue reductions of up to 2.05% per hour of exposure to the spring frost events

---

* Corresponding author.
E-mail address: wfzhang@cau.edu.cn (W. Zhang).
[1] These authors contributed equally to this study.

https://doi.org/10.1016/j.jclepro.2023.140303
Received 19 September 2023; Received in revised form 15 December 2023; Accepted 18 December 2023

(Dalhaus et al., 2020). Nonetheless, devising strategies to encourage smallholder cash-crop producers to respond effectively to climate change and thus mitigate potential losses is challenging.

Climate adaptation strategies formulated for food systems, such as altering crop types (Vincent et al., 2013), transitioning to new varieties (Tanaka et al., 2015), adjusting tillage practices (Khanal et al., 2017), and implementing crop diversification (Anderson et al., 2020), are less applicable to cash crops than to food crops. This disparity is due to the extended growth and yield periods characteristic of cash crops such as fruit trees. The prolonged cultivation periods and the substantial operational and transaction expenses often prompt smallholders to seek rapid economic returns from their production endeavors (Crowther et al., 2020; Hong et al., 2020). In contrast with staple food crops, which benefit from protective market price systems, procurement policies, and agricultural insurance (World Bank Report, 2022), for cash crop production in developing countries, progress in the development of social protection systems has been limited. Without a systematic farmer's support system, smallholders are vulnerable when confronting climate change and its associated risks. Thus, developing smallholder-adapted climate-resilient systems (SA-CRSs) with a specific focus on cash crop production is becoming increasingly urgent.

Building a climate-resilient production system requires extensive and systematic cooperation so that the synergies among factors can be fully explored (Wijk et al., 2020). For example, Acevedo et al. (2020) defined five categories of factors affecting individual adaptation behaviors based on the climate-smart agriculture (CSA) framework of the FAO (2013). This framework highlights the importance of knowledge and financial support, integrating the specificities of sustainability practice adaptation into sustainable agricultural development policies, programs, and investments. However, the transition of CSA into on-the-ground implementation poses a formidable challenge. This endeavor necessitates not only cutting-edge technologies and agricultural methods but also the integration of market-oriented community governance at the local level, establishing incentives and enabling the execution of actions by local stakeholders. These preconditions (or prerequisites) led to the expansion of CSA becoming unfeasible, particularly because smallholders continue to constitute the dominant farming demographic in many developing countries, and market conditions remain underdeveloped (Jiang et al., 2018). Thus, customizing a framework to guide climate adaption responses in the smallholder cash crop production system is necessary.

Apples (*Malus domestica* Borkh.) have long been one of the most important fruit crops in temperate regions worldwide (Janik E, 2011); they are grown in 96 countries, supporting the respective domestic markets and exports (FAO, 2023). In 2020, global apple consumption represented 13% of the total fruit consumption, making apples the fourth most frequently consumed fruit globally (FAO, 2023). Apples are abundant sources of specific micronutrients, including iron, zinc, vitamins C and E, and polyphenols such as procyanidins, phloridzin, and 5′-caffeoylquinic acid. These nutrients can alleviate micronutrient deficiencies and reduce the risk of chronic diseases, resulting in the well-known adage, "An apple a day keeps the doctor away" (Oyenihi et al., 2022). In China, apples are one of the most economically important fruits (Duan et al., 2017), with more than 50% of the global apple cultivation and production (FAO, 2023). Correspondingly, apple production is the main source of income for more than 4.3 million SAFs in China (Huo et al., 2022).

Low temperature during flowering (LTF) events are increasingly frequent climatic shocks that occur during the flowering period of apple trees. Because apple trees are sensitive to temperature change during this key growth stage, LTF events can heavily affect fruit setting and apple production. Moreover, LTF can cause discoloration, desiccation, and death of the flower stigma; necrosis of the pistil and stamens; and the inability to complete the pollination required to form fruit (Lei et al., 2018; Wang et al., 2015). However, studies have focused on extreme freezing disasters in apple production (Dalhaus et al., 2020), and the adverse effects of long-term low temperatures on farmers have been underestimated.

The research objective was to explore how China's SAFs have adapted to the increasing incidence of LTF. To achieve this purpose, we developed a smallholder-adapted climate-resilient system (SA-CRS) framework based on the literature and then collected more than 500 household questionnaire data from two main apple-producing regions in China (Bohai Bay and the Loess Plateau regions) that constitute 35.9% and 42.7% of the national apple production. Next, we applied the mediation effects method to explore the effects of farmers' climate adaptation practices. On the basis of our results, we have suggested specific policy improvements.

Moreover, this paper presents an innovative climate adaptation framework explicitly designed for cash crops and empirically examines how smallholder systems in two major apple production regions in China respond to the often-overlooked climate stressor, LTF. Our research has substantial implications for climate adaptation strategies in developing countries' cash crop systems and deepens the understanding of climate adaptation frameworks. In the remainder of the paper, we provide the SA-CRS framework in Section 2; describe the study area, data sources, and data processing methods in Section 3; present our main findings in Section 4; provide a discussion and corresponding policy recommendations in Section 5; and propose our conclusions in the final section.

2. Conceptual framework: SA-CRS

This study focused on cash crop smallholders, one of the groups most vulnerable to climate change. Smallholders must confront various challenges in response to climate change while managing the problems of insufficient information and knowledge, constrained resource access, insufficient incentives, and limited capacity to respond to climate change (WFP, 2016). These challenges are especially pronounced for smallholder farmers engaged in cash crop production in a climate change environment.

By drawing on insights from the literature, we designed our SA-CRS conceptual framework to address the challenges when farmers adopt climate resilience strategies and technologies (Table 1). Another study

Table 1
Explanatory variables and their relations to literature.

	Elements	Variables	Literature	Hypothesis effect in this study
i.	Institutional price-enhancing mechanism (IPE)	Number of apple price grades	Autio et al. (2021)	+
		Average price of apples	Dalhaus et al. (2020)	+
ii.	Organizational production support system (OPS)	Organized service	Bizikova et al. (2020)	+
iii.	Public extension system (PE)	Technical training	He et al. (2022)	+
		Low-temperature warning times	Bizikova et al. (2020)	+
iv.	Household demographic characteristics	Education	Acevedo et al. (2020)	+
		Planting experience	Ojo et al., 2021	+/−
		Agricultural labor force	Vincent et al. (2020); Esfandiari et al. (2020); Soglo and Nonvide (2019)	+
		Access to credit	Dang et al. (2019)	+
v.	Orchard Characteristics	Tree age	Duan et al. (2023)	+/−
		Planting area	Esfandiari et al. (2020);	+

posited that the role of the individual is central to climate adaptation, highlighting the role of farmers and their adaptation strategies in response to climate change in agricultural sectors (Greg L., 2014). In this study, we focused on smallholders' practical farming practices to adapt to low temperatures during the flowering period. The adoption behavior of farmers with regard to climate adaptation practices is not solely shaped by their internal individual and farm characteristics. It is also significantly influenced by the governance institutions within the contexts in which they reside.

2.1. *External institutional governance system: organizational production-support (OPS) system, institutional price-enhancing (IPE) system, and public extension (PE) system*

In this study, we identified three key enabling support systems when promoting smallholder adaptation in a climate-resilient system: the i) organizational production-support (OPS) system; ii) institutional price-enhancing (IPE) system, and iii) public extension (PE) system. Enabling an OPS system is the first key element in achieving an SA-CRS. A strong OPS system ensures that smallholders can be organized when accessing resources and credits and can enable a flexible approach, including collective machinery services and the larger-scale purchase of inputs (Bizikova et al., 2020). Second, developing an IPE system that enables smallholder competitiveness in the output market and provides incentives for smallholders to adapt to climate change is necessary (Autio et al., 2021). An IPE system does not indicate that the government or other stakeholders are actively influencing the market price to favor smallholders, but it does provide an institutional channel through which smallholders can potentially participate competitively. For instance, by providing smallholders with a standard quality grading system, governments can actively affect smallholder adoption of certain technologies and farming practices to increase the quality of their products (Carter et al., 2006; Ali et al., 2021; Harjanne et al., 2017). Finally, ensuring farmers' access to climate adaptation technologies and climate change-related information and knowledge is important, which requires establishing an effective PE system (Ojo et al., 2021; Esfandiari et al., 2020; Khanal et al., 2019).

These three governance institutions are closely interlinked and co-supported or constrained farmers' climate adaptation practices. The effective interplay and synergy among different institutions promote a virtuous cycle of the system, collectively advancing climate adaptation practices among farmers. For instance, OPS systems can improve production standardization, improving the agricultural product brands of smallholders and, ultimately, influencing IPE systems via enhanced market sales prices (Nguyen et al., 2020). Additionally, IPE systems can enhance OPS systems via certification, increasing profits and improving smallholder production sustainability (FAO, 2013). PE systems can further enhance the effectiveness of OPS systems by providing advanced information and technologies, which may significantly reduce PE service costs, improving efficacy when serving large numbers of smallholders (Bizikova et al., 2020). However, the absence or inadequacy of institutions can degrade the entire system, impeding climate adaptation practices for farmers. Thus, in summary, these three institutional factors (Fig. 1) can play a significant role in improving smallholder resilience, individually and jointly. In this study, the organized production-support (OPS) system refers to organized services; the institutional price-enhancing (IPE) system refers to the number of apple rice grades and average apple prices; and the public extension (PE) system refers to technical training and low-temperature warning times. We hypothesize that.

H1. Organized service has a positive and significant effect on apple farmers' adoption of climate adaption practices.

H2. Number of apple rice grades has a positive and significant effect on apple farmers' adoption of climate adaption practices.

H3. Average price of apples has a positive and significant effect on apple farmers' adoption of climate adaption practices.

H4. Technical training has a positive and significant effect on apple farmers' adoption of climate adaption practices.

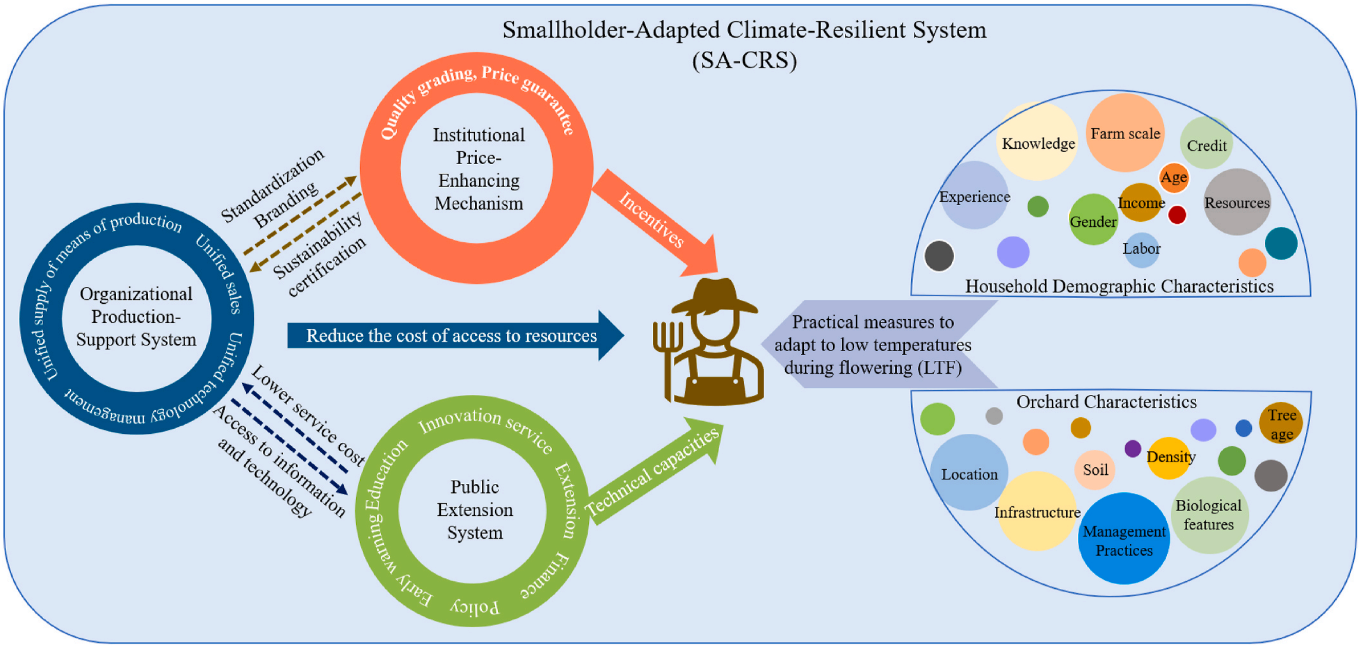

Fig. 1. A conceptual framework for an integrated smallholder-adapted climate-resilience system (SA-CRS). The resilience system is applicable to cash crop systems in developing countries (not limited to apple production) and aims to establish a resilience mechanism for smallholder farmers with mainly cash-crop operations when adapting to future climate change and promoting sustainable development of cash crop systems. The SA-CRS proposes an integrated approach to secure smallholder returns and provide incentives for farmers actively responding to climate change by coupling three subsystems [(i) institutional price-enhancing (IPE) mechanisms, (ii) organizational production-support (OPS) systems, and (iii) a public extension (PE) system] combined with household demographic and orchard characteristics.

H5. Low-temperature warning times have positive and significant effects on apple farmers' adoption of climate adaption practices.

2.2. Internal factors: household demographic characteristics and orchard characteristics

In addition to the external institutional governance system, two subgroups of internal factors are introduced to the framework to consider the importance of individual diversity on climate adaptation: household demographic characteristics and orchard characteristics. We used a method from another study to describe household demographic characteristics, including family endowments such as the agricultural labor force, human capital, farming experience, and financial capabilities. In addition to conventional farm characteristics (e.g., land size, soil quality, and agricultural infrastructure), we integrated specific indicators related to orchard characteristics, for example, factors such as tree age and orchard planting area. These characteristics influence smallholder adaptation strategies by affecting the strength of a farmer's perceptions and attitudes toward climate change and their capacity for implementing certain actions. For example, a more experienced smallholder might have a more accurate perception of climate change and its related events and, thus, might be more likely to implement measures to enhance their climate resilience (Ojo et al., 2021). A household's agricultural labor force and access to credit might further dictate the ability of smallholders to increase their investment in labor and capital when adopting new technologies and farming practices (Vincent et al., 2020; Esfandiari et al., 2020; Soglo and Nonvide, 2019; Dang et al., 2019). These factors might be especially critical for apple production because cultivation is perennial and as the age of trees increases, farmer experience accumulates, and field practices are modified accordingly. Thus, such internal factors are critical for enabling and understanding behavioral change. Household demographic characteristics and operating orchard characteristics have a negative or positive impact on the adoption of climate change adaptation measures by smallholder farmers. The hypothesized effects of household demographic characteristics and orchard characteristics on farmers adaptation behaviors in this study could be shown in Table 1. Overall, we developed this framework based on farmers' climate adaptation practices to explain their adoption of climate adaption behaviors by considering the external community governance and internal individual characteristics of farmers and their farms (Fig. 1). In this study, we applied this framework to SAFs from two main apple-producing regions in China to determine how the adaptation practices reduce the yield loss caused by LTF and which factors influence smallholders' adaptation practices. Several hypotheses were proposed based on the conceptual framework to guide the following data analysis.

3. Materials and methods

3.1. Main apple-producing regions in China and sample selection

There are two major apple-producing regions in China: the Loess Plateau region and the Bohai Bay region (Fig. 2a and Supplementary Data Fig. 1) (Zhu et al., 2018). In 2018, the total apple cultivation area in these two regions was approximately 80% of the entire national production (Zhang Q, 2021). Within these two regions, 122 counties have the highest intensity of apple production, and each key apple county has an area of more than 10,000 ha or annual production of more than 100,000 tons (Ministry of Agriculture and Rural Affairs of the People's Republic of China, 2003). However, there is significant altitudinal

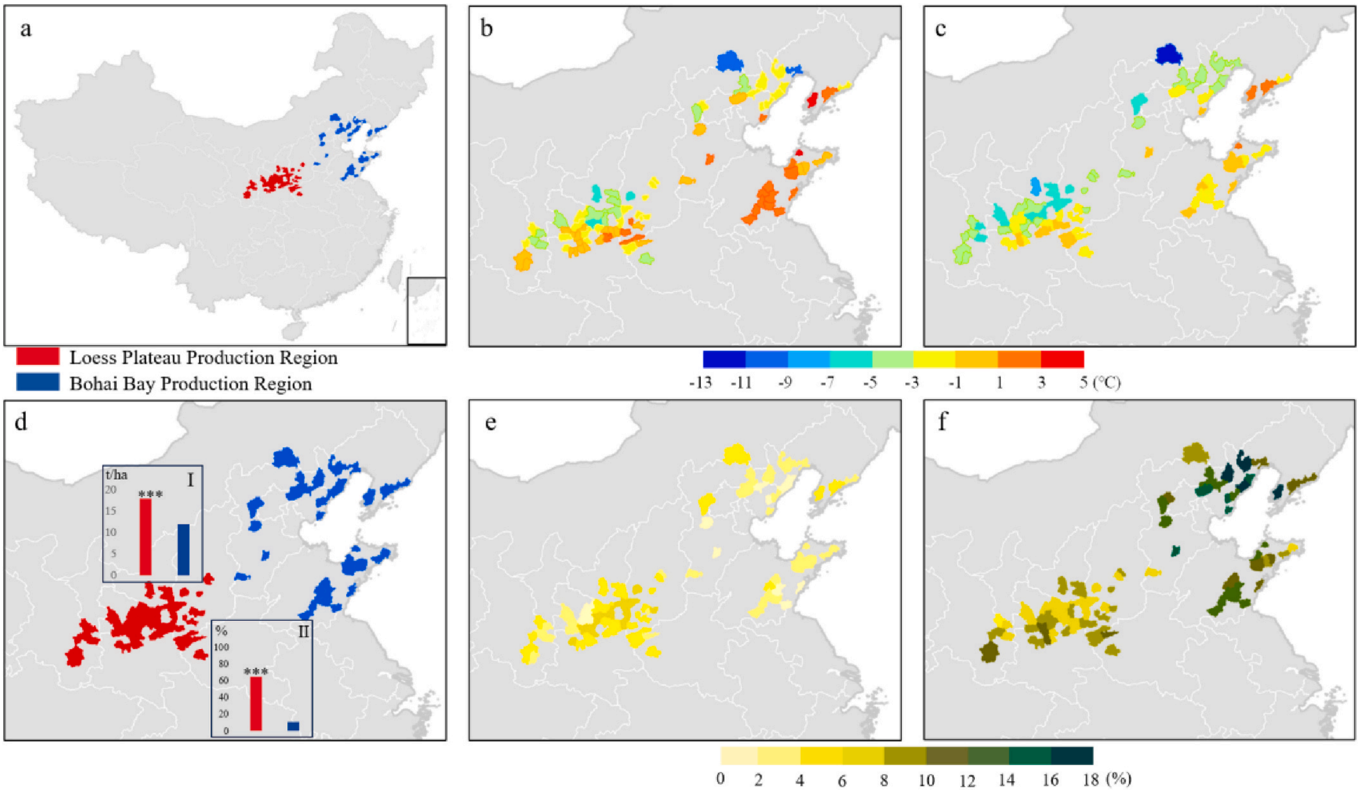

Fig. 2. Low-temperature conditions during apple flowering (LTF) events in dominant apple-producing areas of China, 1999–2018. (a) Distribution of dominant apple-producing areas in China. Blue indicates the Bohai Bay production region and red indicates the Loess Plateau production region. **(b–c)** Daily average minimum temperatures during the apple-flowering period during **(b)** 1999–2008 and **(c)** 2009–2018. **(d)** The proportion of orchards with yield declines and yield decline rates caused by low temperatures in 2018. Graph 'I' shows yield losses (t/ha) caused by the 2018 LTF event, and graph 'II' shows the proportion (%) of orchards experiencing yield declines in the same year. *** indicates statistical significance at $P < 0.001$. **(e–f)** Probability of LTF hazard during **(e)** 1999–2008 and **(f)** 2009–2018. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

variability among these counties, located between 35° and 40° N (Supplementary Data Fig. 1). This difference in altitude results in varying temperatures, with lower temperatures occurring at higher altitudes (Chen et al., 2021). Additionally, under the current trend of global warming, the higher altitude counties are experiencing faster rates of warming (Chen et al., 2018), which increases the risk of early apple tree blooms coinciding with low-temperature events (Fujisawa et al., 2010).

To ensure the representativeness of the selected sample counties, we included counties with annual apple production exceeding 400,000 tons in the two major regions: 12 counties in the Loess Plateau region and 19 counties in the Bohai Bay region. To account for differences in elevation and production, as well as previous low-temperature disaster events, we used a stratified sampling method to select counties from the Loess Plateau region and the Bohai Bay region that had experienced low-temperature damage in 2013 (CMA, 2014) (Supplementary Data Fig. 1), including Luochuan, Baishui, and Jingning in the Loess Plateau region, and Rongcheng, Penglai, Zhaoyuan, Qixia, and Yiyuan in the Bohai Bay region (Supplementary Data Table 2 and Supplementary Data Fig. 1). After these counties were selected, two to three meetings were held with the fruit industry departments of the local county governments. Next, three major apple-producing towns were randomly selected in each county, with two villages randomly selected in each township. Within each village, 12 farmers were randomly selected for a face-to-face questionnaire, and 575 valid samples were obtained.

3.2. Data collection

To measure the occurrence of low-temperature events during the apple flowering period, we consulted apple professionals from different study areas regarding the duration of the local apple flowering period. On average, in both study regions, the flowering period was approximately 15 days. Therefore, we collected temperature data (mainly low-temperature data during flowering) for the last 20 years (i.e., 1999–2018) for 15 days of flowering in 122 major producing counties. To determine the orchard-specific LTF events, we collected all altitudinal data (i.e., mountains, slopes, flats, and depressions) in each village and the surveyed orchards by using Google satellite maps (Google Satelliet Map, 2022). Landform information for each of the surveyed orchards was obtained via a farmer questionnaire, allowing us to approximate the altitude of each orchard.

We conducted face-to-face questionnaire interviews with farmers in July 2019, each lasting approximately 50 min. This method allowed us to collect apple yield data for each orchard for five (2014–2018), which we used to analyze the yield losses caused by the LTF event in 2018. These yield data refer to actual apple production in each current year (i.e., including commercial fruit and retained fruit) and were based on each of the farmers' responses.

The adoption of climate adaptation practices by farmers was determined to evaluate both the uptake and effectiveness of climate adaptation practices in mitigating apple yield losses. We investigated the following six practical measures aimed at reducing the risk posed by LTF during apple production: autumn fertilization, orchard grassing, tree tray mulching, early spring irrigation, orchard fumigation, and Osmia-pollination. A detailed explanation of these practical measures is provided in Supplementary Data Table 1.

According to our conceptual framework (Fig. 1), we collected data on household demographic characteristics (planting experience, education level, number of agricultural laborers, and access to credit in 2017), orchard characteristics (fruit variety, orchard area, and tree age), and the participation of farmers in production organizations (membership in cooperative production and enterprise production). These variables were crucial explanatory variables that influenced the uptake of the different climate-related adaptation techniques outlined in our conceptual framework. Next, we collected data on PE systems (including farmer participation in training and the number of low-temperature warnings issues) and IPE mechanisms (price grading and average sales prices for each county in 2017). The number of low-temperature warnings for each county was obtained through the official county government website. In addition to all the orchards growing the variety "Fuji", 11 indicators in five-factor categories were identified in the questionnaire research. In addition, to assess the revenue status of farmers in these two regions, we identified the selling prices and first-grade fruit production rates of the surveyed SAFs in 2018. First-grade fruits were defined as those with a diameter ≥80 mm, coloring ≥75%, and surfaces free from disease spots. We also determined implementation cost data for each adaptation measure (Supplementary Data Table 6) to assess the sustainability of apple production in the two regions supported by the different resilient systems.

3.3. Data analysis

3.3.1. Low-temperature hazards in apple orchards

The occurrence of low temperatures during the flowering periods was frequent; however, apple flowers are only harmed when a low-temperature threshold is exceeded. We first recorded the lowest temperature of each year during the apple flowering periods as $\mathrm{T}_{\mathrm{j}}^{\mathrm{min}}$, where j denotes different years from 1999 to 2018. Next, we summed the lowest temperature of each year and further divided it by 20 so that we could calculate the average lowest temperature of the past 20 years as $\mathrm{T}_{\mathrm{min\_15}}^{\mathrm{ave}}$ (Equation (1)).

$$T_{min\_15}^{ave} = \frac{\sum_{j=1999}^{2018} T_j^{min}}{20}, j = 1999, 2000, 2001, \ldots, 2018 \tag{1}$$

After we calculated the average lowest temperature during the apple flowering period of 15 days, we could count the actual number of days with daily minimum temperatures below $T_{min\_15}^{ave}$ during the 15 days flowering period of each year, denoted as D_j^{haz}. The ratio of days that has a minimum temperature below $T_{min\_15}^{ave}$ during the 15 days flowering period is the probability of low-temperature hazards occurring in each year, referred to as P_j^{haz}.

$$P_j^{haz} = \frac{D_j^{haz}}{15} \times 100\%, j = 1999, 2000, 2001, \ldots, 2018 \tag{2}$$

By using this approach, we calculated the actual presences of low-temperature hazards in each year over the past 20 years (Fig. 2e and f). However, when calculating the incidences of LTF events at the orchard level, we must further consider the change in the altitudes, particularly in counties with a significant variation in altitude.

We calculated the orchard level incidence of LTF (TO_{ij}^{min}) with the condition of its altitude (with temperature decreasing by 0.6 °C for every 100 m increase in elevation). First, we calculated the lowest temperature during the flowering period in 575 orchards in 2018 according to equation (3).

$$TO_{ij}^{min} = T_{ij}^{min} - \frac{\left(ALT_i^O - ALT_i^C\right)}{100} \times 0.6, j = 2018 \tag{3}$$

where i denotes orchard i at county c, T_{ij}^{min} is the county minimum low temperature in 2018, ALT_i^O is the orchard i altitude, and ALT_i^C is the county average altitude. When $TO_{ij}^{min} \leq T_{min\_15}^{ave}$, the orchard was classified as being threatened by the low-temperature event in 2018. Next, we counted how many orchards within a county were threatened by the LTF, denoted as $DO_{\mathrm{j}}^{\mathrm{haz}}$. We found that 554 orchards were threatened by low temperatures in 2018, with 21 orchards in Jingning County unaffected.

$$PO_{\mathrm{j}}^{\mathrm{haz}} = \frac{DO_{\mathrm{j}}^{\mathrm{haz}}}{n} \times 100\%, \mathrm{j} = 2018 \tag{4}$$

where n denotes the number of orchards per county. In each county except for one, we sampled 72 orchards, in Luochuan County, we sampled 71 orchards. The ratio of the number of orchards threatened by this low-temperature event to the total number of samples in each county was then defined as the proportion of low-temperature orchards, denoted as PO_j^{haz} (Supplementary Data Table 3).

3.3.2. Low-temperature resilient farming practices and smallholder technology adoptions

Apple yields are influenced by a combination of management, climatic, and soil conditions. Thus, to determine the effect of climatic conditions on apple yield, we evaluated yield variability during 2014, 2016, and 2017, and found that no low temperatures had occurred (Supplementary Data Fig. 2). Yield variability over these three years was, therefore, attributed to differences in management and soil properties. Overall, the decline in yield associated with the 2018 LTF event was 8.8% relative to the three years 2014, 2016, and 2017, which we attributed to low-temperature damage during apple flowering and fruit set. Although this overall decline in yield appears relatively low, adopting low-temperature adaptation techniques can help stabilize (and possibly increase) yields in these vulnerable regions.

The calculated yield decline was defined as the low-temperature yield losses, denoted as Y_{loss}, and an orchard that experienced low temperatures and a decrease in yield was defined as OY_{loss} of which there were 165 orchards, including 40 orchards in the Bohai Bay and 125 orchards in the Loess Plateau production areas. The percentage of orchards in the different study regions that experienced low temperatures and yield losses are shown in Fig. 2d (graphs I and II).

$$Y_{loss} = Y_{mean} - Y_{2018} \tag{5}$$

where Y_{2018} is the apple yield in 2018, and Y_{mean} is the average yield for the three years 2014, 2016, and 2017.

During apple production, farmers often use various practical measures to minimize the damage caused by low temperatures and to ensure stable yields (Supplementary Data Table 4). Therefore, we analyzed the variation in yields in 2018 for the 554 orchards that experienced low temperatures, denoted by ΔY:

$$\Delta Y = Y_{2018} - Y_{mean} \tag{6}$$

where Y_{2018} is the apple yield in 2018, and Y_{mean} is the average yield for the three years 2014, 2016, and 2017.

Although most studies have confirmed the role of these management practices in preventing LTF events (Li et al., 2009; Bizikova et al., 2020; Autio et al., 2021), they have not compared the prevention effects of different management practices. Notably, the integrated effect of multiple management measures is frequently more effective than single measures. Therefore, to evaluate the integrated effect of multiple management measures, we determined those farms that employed 0, 1–2, 3–4, or 5–6 of these practical measures and compared these data with reported apple yields.

3.3.3. Empirical model and relative importance analysis

The data in this study were cross-sectional, and to investigate the mediating role of the number of technology adoptions between the resilience system and yield value added, we proposed the following model, drawing on the testing process proposed by Wen and Ye (2014). The adoption of the mediated modeling approach expresses the causal relationship among the resilience systems, the number of technologies adopted by farmers and yield value added.

In the first step, model (7) was constructed to test whether the resilience system could influence the yield value added:

$$\Delta Y = \alpha_1 + \beta_1 Res_i + \varepsilon_i \tag{7}$$

In the second step, model (8) was constructed to test whether the resilience system could influence the number of technology adoption by farmers:

$$Tec_i = \alpha_2 + \beta_2 Res_i + \varepsilon_i \tag{8}$$

In the third step, model (9) was constructed by testing the mediating effect of the number of farmers' technology adoption in the relationship between the resilience system and the yield and the yield value added:

$$\Delta Y = \alpha_3 + \beta_3 Res_i + \lambda Tec_i + \varepsilon_i \tag{9}$$

where i denotes farmer ith; $\alpha_1, \alpha_2, \alpha_3$ represent the constant term to be estimated in each model; ΔY are outcome variables indicating yield value added, the detailed calculation method is shown in Equation (6); Res_i denotes the explanatory variable, namely, the relevant influencing factors in the resilience system, which are the education level of the head of the household (years), the farming experience of the head of the household (years), the total number of laborers within the household, access to credit within the household in the past year, tree age (years), the total planting area of Fuji apples (ha), technical training (whether farmers had attended public or private training on management measures for the prevention of low-temperature risks; 1 = yes; 0 = no), low-temperature warning information (number of times a warning was issued, as published on the websites of local fruit management departments before the onset of the 2018 LTF event), organized services (whether the farmer had joined an industrial organization such as a cooperative or company; 1 = yes; 0 = no), the average sales price (RMB/kg) and the number of sales grades (grades) in each county in 2017 (Supplementary Data Table 5); Tec_i denotes the mediating variable, namely, the number of technologies adopted by farmers (which refers to the total number of orchard grassing), tree tray mulching, autumn fertilization, early spring irrigation, orchard fumigation, and Osmia-pollination adopted by farmers in 2018; and β_1 denotes the effect of the resilience system on yield value added in model (7); β_2 denotes the effect of the resilience system on the number of technology adoption by farmers in model (8); β_3 denotes the effect of the resilience system on yield value added in model (9); λ denotes the effect of the mediating variable (the number of technology adoptions) on yield variation in model (9); and ε_i is the random perturbation term. The description of each variable and the descriptive statistics are shown in Supplementary Data Table 7.

To further explain the causal relationship between the different variables, we adhere to the principle of causality within the realm of social sciences (Morgan, S. L. and Winship, C., 2015). Grounded in the notion that causes precede effects, we delineate the relationships among the indicators in this study. The average price of apples and the sales grade figures in 2017, as discussed in our study, indisputably occurred prior to farmers obtaining apple yields in 2018. Similarly, other indicators such as the frequency of low-temperature warnings, participation in technical training, and engagement in organizational services also transpired before the apple production in 2018. Furthermore, the mediating variable posited in our model—the number of technologies adopted by farmers—likewise pertains to the pre-yield adoption of technologies. Consequently, the interplay of indicators in this study aligns with the principle of causation, where causes precede effects. The principle of causality in social sciences encompasses causal co-variation as well. In our study, the fluctuations in market prices in 2017 impact the adoption of technological measures by farmers. Concurrently, changes in farmers' technological adoption contribute to variations in apple yield. Additionally, alterations in the other independent variables considered in this study result in corresponding changes in the outcome variable, thus affirming adherence to the principle of causal co-variation. The third principle is to exclude other explanations except causal relationships, such as interaction relationships. It is obvious that there is no interaction between market prices in 2017 and production in 2018 in this study.

In addition to the principle of causality in the social sciences, we employed the causal mediation analysis method to validate the traditional mediation effects. The validity of causal mediation effects hinges on adherence to the serial negligibility assumption, though its verification using observed data remains unattainable. We acknowledge the presence of confounding factors, and the evaluation of the extent to which these confounders may influence the mediating effect necessitates additional sensitivity analysis (Imai et al., 2011).

A relative importance analysis was performed based on regression analysis (Ye et al., 2015; Israeli O, 2006). Therefore, relative importance analysis was used to analyze the effect of factors in the resilient system on the number of technology adoption by farmers. First, the R^2 value related to the number of adaptation measures adopted was obtained. Second, the value was decomposed for each impact factor. Finally, the relative importance of each variable relative to the dependent variable (i.e., the number of measures adopted) was determined. All analyses were performed using stata15.

3.4. Statistical analysis

All estimated parameters were based on analysis of variance using IBM SPSS statistical software version 22. Duncan's least significant difference test was used to compare the mean records, with a significance level of 5%, 1%, and 0.1%. Model estimation and relative importance were analyzed using stata15.

4. Results

4.1. LTF events in China and their effect on SAF apple production

From 1999 to 2018, the magnitude of LTF events in the main apple-producing regions of China (including 122 counties) increased. During this period, the average daily minimum temperature decreased by 1.77 °C overall (−0.91 °C in 1999–2008 and −2.68 °C in 2009–2018; Fig. 2b and c). This dramatic drop in minimum temperatures is beyond the tolerance threshold of apple flowers, leading to an increased probability of low-temperature hazards during the apple-flowering season.

We found that the probability of LTF hazard increased from 4.3% in 1999–2008 to 10.4% in 2009–2018 (Fig. 2e and f, Supplementary Data Fig. 3). In the Loess Plateau region, the minimum daily temperature decreased by 1.71 °C, and the LTF hazard probability increased from 5.2% to 8.6% (+3.4%). In the Bohai Bay region, the minimum daily temperature decreased by 1.85 °C, and the LTF risk increased from 3.2% to 12.8% (+9.6%) (Fig. 2b, c, 2e, 2f). In 2018, some of the sampled counties (eight typical counties) in these regions experienced an extreme LTF event, such as the −5 °C event in Luochuan County (Supplementary Data Fig. 2).

Because temperature differences partly correspond to altitude, LTF hazards can vary among orchards in the same county. Therefore, we determined whether individual orchards were threatened by LTF events based on the relationship between altitude and temperature (see Methods for details). Among the 575 surveyed SAFs, 21 SAFs in Jingning county were unaffected by LTF events during the apple production periods in 2018, and the remaining 554 SAFs (96.3% of those sampled SAFs) were adversely affected by at least one LTF event (Supplementary Data Table 2).

LTF events in the studied regions have been associated with sharp declines in apple yields, although losses vary by region. By calculating the coefficient of variation in yield among 2014, 2016, and 2017 (when no LTF events occurred), we determined that an overall yield decline of more than 8.8% was associated with the 2018 LTF event (see Methods for details). We found that 165 SAFs experienced declines in yield, accounting for 29.8% of those who experienced the LTF event (554 SAFs). For those SAFs experiencing losses, apple yields decreased by an average of 16.43 t/ha (Supplementary Data Table 3). In the Loess Plateau region, 64.4% of the farmers experienced yield losses due to the LTF event, resulting in an average yield loss of 17.85 t/ha for the same event, the proportion of farmers experiencing yield losses (11.1%) and the average yield losses (12.00 t/ha) were significantly lower in the Bohai Bay region than in the Loess Plateau region (Fig. 2d).

4.2. Adopting practical measures to address LTF risks and mitigate yield losses

The adoption of farming practices to manage LTF events helps reduce yield losses, as shown by the difference between yields in 2018 and the average yield during three years (2014, 2016, and 2017, see ΔY in the Methods), and adopting multiple management measures is more effective than adopting single measures in this respect (Supplementary Data Fig. 4). Among the 554 orchards that experienced LTF events, there were differences in the adaptation measures used and corresponding yield changes. For the 554 SAFs who experienced LTF events, yield losses decreased when adequate practical measures were adopted, and yield increases were achieved when five to six measures were adopted (Fig. 3). In the Bohai Bay region, apple yields were unaffected by the adoption of one or two practical measures, and in the Loess Plateau region, yield losses were avoided when at least five practical measures were adopted (Fig. 3). Overall, 90.0% and 30.4% of the SAFs in the Bohai Bay region and the Loess Plateau region, respectively, adopted at least three adaptive practices during the study period (Fig. 3). Notably, the adoption of the same number of adaptive practices had less effect on LTF losses in the Loess Plateau than in the Bohai Bay region. This finding partly occurred because fewer farmers applied the other seven practical measures (thinning flowers, thinning fruits, orchard pruning, bagging and bag-removing, topdressing, spraying pesticides, and laying reflective film) throughout the apple production season in the Loess Plateau region (73.4% adoption) than in the Bohai Bay region (91.0% adoption; Supplementary Data Table 4). Although these seven practical measures did not directly prevent LTF, they supported high yields. For example, orchard pruning increases yields by facilitating the formation of fruit-bearing branches and encouraging fruit trees to produce flower buds and fruits in spring. Topdressing supports high yields by fulfilling the nutrient requirements of late fruit growth, promoting fruit expansion and increased fruit weight.

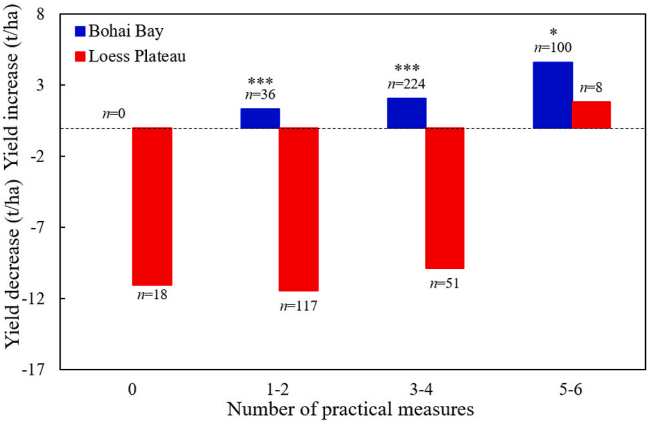

Fig. 3. Relationship between the number of climate change adaptation measures adopted by smallholders and changes in apple yields in two dominant appleproducing regions of China (see Methods for a full explanation of ΔY). When the fruit farmer does not take any practical measures, it is defined as 0. When the fruit farmer adopts any one or two of the six practical measures, it is defined as 1–2. When the fruit farmer adopts any three or four of the six practical measures, it is defined as 3–4. When fruit farmers adopt any five or six of the six practical measures, it is defined as 5–6. Blue indicates the Bohai Bay production area, and red indicates the Loess Plateau production area. *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$. Practical measures 1 to 6 are fully defined in Supplementary Table 2. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

4.3. Factors driving the adoption of LTF-related adaptive practices

Our analysis suggests that the adoption of various practices helped mitigate yield losses during the study period and that the establishment of resilience systems helped improve farmers' management practices. Therefore, we selected the mediating effects model to explore the mediating role of the number of technologies adopted by farmers between resilience systems and yield value added (column 1, column 2 and column 3, Table 2), i.e., the resilience system ameliorates yield losses by enhancing farmers' technology adoption. Meanwhile, based on the traditional mediated effects analysis, causal mediated effects analysis was further used to validate the mediated effects results (column 4, column 5, Table 2). Our findings demonstrate that the mediating effect persists as robust, affirming the existence of causality despite the acknowledged confounders. The following results were obtained with reliable modeling results.

First, we analyzed the effects of the factors in the resilience system on yield value added. Among these factors, the number of price grades and the average price in the price-enhancement mechanism showed a positive effect on yield value added (the regression coefficient is significantly positive at the 1% level) (column 1, Table 2), namely, as the price-enhancement mechanism improved, yields showed a positive increase (higher yields). The number of low temperature warnings also showed a positive effect (regression coefficient significant at 5% level). By contrast, farmers' planting experience showed a negative effect (at 10% level) (column 1, Table 2) probably because experienced farmers tend to use management practices with which they are familiar and which are not effective in managing climate change and ensuring yields.

Second, we analyzed the effect of factors in the resilience system on the number of technology adoption by farmers. The results showed that the number of price tiers and the average price in the price enhancement mechanism had a positive effect on the number of technology adoptions by farmers (significantly positive at the 1% level), namely, the improvement in the price-enhancement mechanism enhanced the adoption of adaptive measures by farmers. Low-temperature warnings were also important for farmers' technology adoption (significantly positive at the 10% level), and when the number of low-temperature warnings increased, farmers' climate change perception improved, which enhanced technology adoption. Farmers' education level had a significant positive effect (significant at 1% level) on inducing their technology adoption, indicating that improving education increased the farmers' knowledge and understanding of climate change risks and, thus, motivation to adapt. Planting area and organizational services also showed positive effects on enhancing technology adoption by farmers (significant at the 5% and 10% level, respectively) (column 2, Table 2), the causal mediation analysis also obtained similar results (column 4, Table 2).

Finally, we verified the mediating effect of the number of farmers' technology adoptions. The regression analysis found that the number of technology adoptions had a significant positive effect (significant at 5% level) on yield value added (column 3, Table 2). According to the stepwise regression mediation effect test criterion, the number of technology adoptions played a mediating role between the resilience system and yield value added, namely, the resilience system achieved yield enhancement by enhancing farmers' technology adoption. In addition to the proven mediating effect of the number of technology adoptions, the number of price tiers and average price in the price enhancement mechanism showed a positive effect (significant at the 1% level) on yield value added. The number of low-temperature warnings likewise showed a positive effect on yield value added (significant at the 5% level); by contrast, farmers' growing experience showed a negative effect on the value added to apple yield (significant at the 10% level) (column 3, Table 2), the above results were likewise validated by causal mediation effect analysis (column 5, Table 2).

Based on an assessment of the relative contribution of the different factors using R^2 values (Ye et al., 2015; Israeli O, 2006), the two IPE measures explained 84.0% of the variation in the uptake of climate change adaptation measures (43.7% for the number of price grades and 40.3% for the average price), OPS measures accounted for 3.8%, and the education level of SAFs accounted for 5.3% (Fig. 4).

4.4. A virtuous or vicious circle? Climate shocks, adaptation, and system resilience

Climate shocks might push a poor, resilient agricultural production system into a vicious circle. When there is a relatively strong resilience system in apple production, the influence of climate shocks might decrease, and the damage due to climate shocks can be mitigated

Table 2

Analyzing the mediating role of the amount of technology adoption by farmers between resilience systems and yield value added.

	(1)Yield value added	(2)Number of technology adoptions	(3)Yield value added	(4)Number of technology adoptions	(5)Yield value added
Number of technology adoptions			0.9080** (2.3119)		0.9080** (2.31)
Institutional Price-Enhancing Mechanism					
Number of apple price grades	5.8390*** (8.30)	0.5157*** (4.91)	5.3708*** (7.14)	0.5157*** (4.82)	5.3708*** (5.37)
The average price of apples (RMB/kg)	3.0855*** (4.04)	0.4877*** (4.31)	2.6427*** (3.35)	0.4877*** (4.38)	2.6427*** (2.55)
Public Extension System					
Technical training (1 = yes; 0 = no)	−0.4388 (0.40)	−0.0537 (0.46)	−0.3901 (0.36)	−0.0537 (0.45)	−0.3901 (0.36)
Low-temperature warning times	1.2586** (2.18)	0.1097* (1.70)	1.1590** (2.01)	0.1097* (1.68)	1.1590** (1.93)
Household demographic characteristics					
Education (years)	−0.1384 (0.87)	0.0496*** (2.66)	−0.1835 (1.13)	0.0496*** (2.60)	−0.1835 (1.04)
Planting experience (years)	−0.1220* (1.82)	−0.0100 (1.25)	−0.1130* (1.70)	−0.0100 (1.35)	−0.1130* (1.67)
Agricultural labor force	0.8679 (0.86)	−0.1108 (1.07)	0.9685 (0.95)	−0.1108 (1.04)	0.9685 (0.99)
Access to credit	−0.0294 (0.03)	0.0277 (0.22)	−0.0546 (0.06)	0.0277 (0.21)	−0.0546 (0.05)
Orchard characteristics					
Tree age (years)	−0.0129 (0.19)	−0.0013 (0.16)	−0.0117 (0.18)	−0.0013 (0.18)	−0.0117 (0.17)
Planting area (ha)	0.0090 (0.77)	0.0034** (2.15)	0.0058 (0.52)	0.0034** (1.39)	0.0058 (0.26)
Organizational Production-Support System					
Organized service (1 = yes; 0 = no)	−0.2662 (0.28)	0.2194* (1.96)	−0.4654 (0.50)	0.2194* (1.97)	−0.4654 (0.46)
Constant	−31.7886*** (7.94)	−0.5999 (1.53)	−31.2439*** (7.76)	−0.5999 (1.43)	−31.2439*** (8.13)
R^2	0.285	0.325	0.292	0.325	0.292

Note: The resilience system refers to 11 factors in 5 parts. The absolute value of t is in parentheses; ***, **, *indicate statistically significant at the 1%, 5%, and 10%, respectively. The total number of observations is 554.

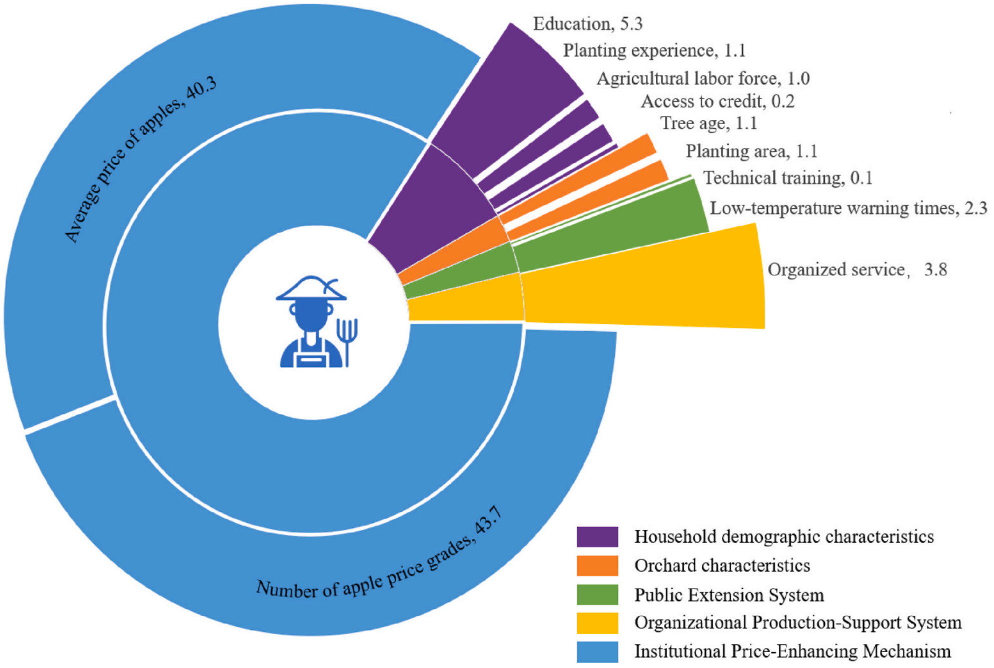

Fig. 4. Relative importance of different factors influencing the number of practical adaptation measures adopted by smallholders in China. Purple indicates household demographic characteristics, orange indicates orchard characteristics, green indicates public extension systems, yellow indicates organizational production-support systems, and blue indicates institutional price-enhancing mechanisms. Household demographic characteristics include education level, planting experience, agricultural labor force, and access to credit. Orchard characteristics include tree age and planting area. Public extension systems include technical training and low-temperature warnings. Organizational production-support systems refer to organized services for smallholders. Institutional price-enhancing mechanisms include the average price of apples and the number of apple price grades. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

effectively. Our field interviews demonstrated that, overall, the Bohai Bay region has a relatively well-established climate-adapted resilient system of apple production, and the system in the Loess Plateau region is relatively poorly developed. For instance, SAFs from the Bohai Bay region adopted an average of 3.86 adaptation practices (as listed in the survey), and 15.3% of the SAFs in this region reported yield losses due to LTF events. A local apple farmer [in Bohai Bay region] told us, "LTF events can have huge damage if they have no expectations or early warnings. However, when there are some early warnings from the local agricultural department or extension support, we can effectively prevent such damage. It might cast some negative impact, but the magnitude will be much less severe."

Notably, during the study period in 2018, SAFs in the Bohai Bay region achieved relatively higher yields (approximately 41.81 t/ha, average yield of the sample orchards) than those in the Loess Plateau region (13.49 t/ha). As we expected, SAFs in the Loess Plateau region adopted an average of 2.01 recommended adaptation practices (Table 3). Regarding apple quality, 60.4% of the apples produced in the Bohai Bay region were of premium quality, and the per unit price was as high as 6.26 RMB/kg (Table 2). Apple quality in the Loess Plateau region was comparatively low, with 28.7% of the apples being premium quality and an average per unit price of 5.08 RMB/kg. Despite the considerable variation in the average unit price of apples across the two regions, the price of apples of the same grade remained relatively stable. For instance, the unit price of 70–75 grade apples was RMB 3.2 in Yiyuan County and RMB 3.0 in Jingning County (Supplementary Data Table 5). According to the wholesaler and other interviewed apple agribusiness owners, "There were limited price differences among the premium quality apple either from the Bohai Bay region or from the Loess Plateau; however, there was significant short of premium quality apple from the Loess Plateau region compared with the Bohai Bay region. We have got much more premium quality apple (further with different rankings among premium quality apple) supply from Bohai Bay region."

Table 3
Evaluation of the effect of different resilient systems (good and poor) on smallholder apple farmers (SAFs) in two apple-producing regions of China.

Indicators	Well resilient system support (Bohai Bay)	Poor resilient system support (Loess Plateau)
	(n = 360)	(n = 194)
Number of practical measures adopted	3.86 ± 1.06***	2.01 ± 1.24
The average yield of the sample orchards (t/ha)	41.81 ± 22.56***	13.49 ± 14.21
Percentage of first-grade fruits (%)	60.4 ± 28.5***	28.7 ± 20.6
The average sales price in 2018 (RMB/kg)	6.26 ± 2.17***	5.08 ± 1.63
Apple revenue of SAFs in 2018 (RMB/ha)	270,018 ± 195,507***	76,235 ± 104,943
Per capita income in 2018 (RMB)	44,553 ± 32,269***	12,579 ± 17,316

Note: Due to the well-established price mechanism, public extension services, and better organizational support in the Bohai Bay production area, we compared the Bohai Bay production area with the Loess Plateau region as regions well and poor resilient system, respectively. T-tests were performed based on "Loess Plateau" as the reference. *, **, and *** indicate statistical significance at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

In this context, we used SAFs' yields and market prices to calculate their total apple revenue; that in the Bohai Bay region (270,018 RMB/ha) was almost four times higher than that of the Loess Plateau region (76,235 RMB/ha) (Table 3). The high returns support the operating costs of the practice, and social security increases smallholder revenues through enhanced action, guaranteed prices, and higher yields, gradually creating a virtuous circle. In the Loess Plateau region, the per capita income of fruit farmers (RMB 12,579) was approximately one-third of the per capita income (Table 3). As such, SAFs in the Loess Plateau region are constrained by the high operational costs of adopting the LTF-related adaptation practices (10.1% higher than the technical operational costs in Bohai Bay, Supplementary Data Table 6), low returns cannot support the costs of practical activities and weak social protection, which fuel a vicious cycle of hazard vulnerability and insufficient practice adaption or inaction.

5. Discussion

5.1. Hazards of low-temperature events during apple flowering

Managing climate change and ensuring fruit production are essential to achieving global food security and several of the United Nations' sustainable development goals. Studies have explored the containment of apple production in terms of unsuitable temperature changes such as winter warming and high summer temperatures (Zaller et al., 2023; Parkes et al., 2020). However, additional research on the threat to apple production from low-temperature events during flowering is urgently necessary. We used low-temperature events during apple flowering in China to clarify the threat of low-temperature events in the spring to yield in the main apple-producing regions of China. Low temperatures during flowering in 2018 resulted in a yield loss of 16.43 t/ha, and similar results were supported by related disaster reports, such as the expected 42.6% reduction in commercial fruit production across the country, according to apple bagging data from China Apple Network in 2018. The main reason for the significant decline in yield is flower failure triggered by low temperatures in the spring. Studies have shown that when there are low-temperature cold waves, the pistil in the floral apparatus is the least cold-tolerant part and can be harmed by slightly low temperatures (Rodrigo J., 2000), and although the flower can open normally, it cannot complete the fertilization of the fruit and ultimately result in a loss of yield.

In addition, as global climate change continues to intensify, the risk of low temperatures during the flowering period of apples is increasing. There are two main reasons for this result: on the one hand, the increase in winter temperature forces apple cultivation to gradually extend to higher altitude areas, where temperature changes are drastic, and the fluctuating high and low temperatures increase the risk of low temperatures during flowering (Delgado et al., 2021); on the other hand, climate warming will lead to an advance in the flowering time of apples, and the literature has shown that warming-induced apple flowering has advanced by 0.21–0.35%. Some studies have shown that warming causes apple blossom to advance by 0.21–0.35 days/year, and the advancement of blossom increases the overlap between apple blossom time and spring low-temperature events, which increases the risk of experiencing low temperatures (Pfleiderer et al., 2019). Thus, apple production in China must strengthen its response to low temperatures during flowering to achieve sustainable development.

5.2. Effects and drivers of adaptive measures by smallholder farmers

The positive effects of different management practices for adapting to low temperatures during flowering have been demonstrated; for example, physical adaptations (e.g., antifreeze spraying and artificial heating) have significant effects in protecting apples from low temperatures (Unterberger et al., 2018). In smallholder practices in China, management measures such as early spring irrigation and orchard fumigation are commonly used to manage low temperatures during flowering, and studies have focused on the analysis of the effects of a single practice (Anconelli et al., 2002; Ribeiro et al., 2006) but not analyzed the integrated effects of multiple practices.

We quantified the effects of multiple practice measures on yield loss by summarizing six commonly used management practices and grouping them. The results indicate that adopting multiple management practices is more effective in avoiding yield loss than adopting a single practice, and when the number of practice measures adopted reaches 5–6, yield loss is prevented, and yield increase is achieved. This study also demonstrated that a combination of management practices is much more effective in increasing yields than a single technical measure (Zhang et al., 2016).

In practice, not all smallholders adopt practical measures to manage low temperatures during flowering. Our study found that 96.8% of the farmers adopted one or more practical measures, and 19.5% of the smallholders adopted more than five practical measures. The main reason for this difference is insufficient incentives. In our proposed conceptual framework, based on previous research, it is clarified that household demographic characteristics and orchard characteristics are intrinsic factors that influence smallholder climate adaptation decisions. In addition, we hypothesize that effective organized production system, a well-developed price promotion system and a sound public extension system play a positive role in the adoption of climate adaptation decisions by farmers, and these hypotheses (H1–H5) are verified in the results analysis. For example, cash crops have a higher value than food crops and can provide economic support to farmers; thus, crop prices can severely constrain the adoption of climate adaptation measures (Jeffrey et al., 2005). The price of apples is generally determined by quality grading: different prices are set according to the size of the fruit. If the fruit is small and the price is low, the lack of available assets reduces the willingness of smallholders to manage orchards (Zhang et al., 2023). Smallholders should be encouraged to move from low-quality to high-quality products, which depends largely on field practices, including input use, farm management, and local climatic conditions (Luning et al., 2007; Milošević et al., 2022). Additionally, the price that accompanies quality fruit needs to be guaranteed; otherwise, it can create psychological barriers for farmers and lead to a negative attitude toward cultivation. For example, the decline in agricultural prices and incomes may explain 10–30% of the decline in production in the United States in 1930 (Hausman et al., 2021). We also posit that if high-quality fruits are not guaranteed higher prices than low-quality fruits, farmers are likely to become negatively disposed to agricultural production. However, raising prices without proper planning may not be a long-term solution, and building a resilience system based on price guarantees may be more feasible than that plan.

Second, organizing production also plays a positive role in the adoption of adaptive measures. We found that approximately 32.5% of all smallholder farmers joined some form of cooperative or agribusiness and that cooperatives provided farmers with integrated service support throughout the production process to fulfill the IT information needs of smallholder farmers. A well-functioning cooperative organization can increase smallholder farmers' investment in production, regulated farming, market access, and price stability (Blekking et al., 2021; Mangnus et al., 2020). For example, a cooperative organization can provide apple smallholders with specialized production materials and standardized operations to achieve stable product output. However, the size of the cooperative organization needs to be considered, and relatively larger cooperatives can provide lower-cost services to farmers (Gezahegn et al., 2019). The effect of the public service system on the adoption of adaptive measures was not observed in this study, and notably, public services can provide smallholder farmers with technological innovations, weather information, and policy guidance (Buadi et al., 2013; Haigh et al., 2018). According to our survey, smallholders can gain technical knowledge on apple management in technical training via public services and can sense temperature changes in advance via cold weather warnings. However, the local government's technical training and weather warning services are relatively weak, for example, the number of low-temperature warnings provided by the government is one per year, and the weak public services do not fully play the role of extension, which may be why the public service effect was not found in this study.

In addition, farm household (education, farming experience, agricultural labor, available credit) and orchard characteristics (age, size) are important factors influencing the adaptation decisions of economic smallholders, which have long been confirmed by studies in different regions (Acevedo et al., 2020; Ojo et al., 2021; Vincent et al., 2020; Duan et al., 2023).

5.3. Challenges in building resilient systems for adaptation to climate change

As our analytical framework shows, three support mechanisms are necessary to establish an effective SA-CRS. One of them, the IPE system, is key to ensuring that smallholder production systems can manage with the risk of low temperatures during flowering. However, how to build a sound IPE system has not attracted much attention in the agricultural community. Studies on agricultural product price security have only focused on price forecasting, not specifying how to build a stable price enhancement system (Mohanty et al., 2023; Ray et al., 2023).

In the case of apple production in China, we posit that local governments should implement several measures. First, an effective quality grading system with a reflective price system should be established. Although there is a national apple-quality grading system in China, due to differences in sales markets, SAFs in different regions often must use different grading systems when selling their apples. For instance, in the Loess Plateau region, SAFs report two grades of apple prices that correspond to quality, and in the Bohai Bay region, SAFs report four grades (Supplementary Data Table 8). Such differences in IPE systems can be attributed to varying public investments in local logistics, apple storage, wholesale market development, and government regulations regarding quality inspection. Second, effective market price monitoring and communication with SAFs are required. Because in cash crops, such as apples, often show very drastic market price fluctuations. Notably, without timely market price monitoring and communication, price volatility can be exacerbated rather than stabilized among SAFs without an effective quality grading system. Under these circumstances, local government involvement in the dissemination of cash crop market price information among stakeholders along the supply chain would be good practice, warning SAFs to take preventive action. Third, building an effective IPE system might also be achieved via regional branding practices. Developing a regional brand will empower SAFs to improve market accessibility and bargaining power and help stabilize regional apple prices.

To establish SA-CRS to manage with the adverse impacts of potential climate shocks, local governments and relevant stakeholders must establish and strengthen local OPS systems, such as multifunctional cooperatives and small- and medium-sized agribusinesses, focusing on production, storage and logistics, and market prices. First, the government should support the development of cooperative organizations through policies, such as providing financial support and legal guarantees; second, it should promote agricultural technological innovation, with research institutes providing new technologies, varieties, and models for cooperative organizations and strengthening technical training and guidance for farmers; finally, it should guide organizations to establish standardized cooperatives, implement professional management models, and improve the operational efficiency of cooperatives. In addition, the public service system should be guaranteed, for example, the government meteorological department can strengthen the low-temperature disaster warning (Frank et al., 2015) and cooperate with communication agencies to release early warning information in the form of text messages; banks and financial institutions can innovate financial products and strengthen credit services (Kumasi et al., 2019); and scientific research colleges and universities can innovate the mode of scientific and technological services to realize the effective technology dissemination and landing.

6. Conclusions

Climate change adaptation and its impacts require the participation of multiple actors, such as governments, research institutions, markets, and cooperative organizations, in climate action, and how to adapt to climate change in cash crop production requires further research. Our research aimed to help cash crop smallholders construct a climate change resilience framework dominated by market systems and supported by cooperative organizations and public services. To achieve this goal, we selected apple production in China as an example, and our empirical analysis proved that a resilient framework with a complete market system promotes a large number of practical measures, reduces yield losses, and supports a virtuous cycle of apple smallholder production. It encourages the development of a high-standard market system and promotes market price stability in terms of basic systems, market opening, and market regulation; supports the development of multifunctional cooperatives by providing a series of preferential policies to cooperatives, such as preferential land transfers and water and electricity costs; and improves the functioning of the public service system by strengthening the subsidies for agro-meteorological disasters and setting up special credits and insurances. The efforts of various stakeholders can help reduce the barriers smallholder farmers experience in managing with the ongoing risks of climate change. By establishing guaranteed market prices, ensuring the availability of technical information, and encouraging organized production, the capacity of farmers to manage climate change will be improved, and the sustainable development of global cash crops will be achieved.

This study provides a resilient framework for adaptation to climate change for smallholder cash crop farmers in developing countries, and further empirical research on cash crop systems is necessary to validate the appropriateness of this framework as climate change continues to intensify. Additionally, this study used cross-sectional data from smallholder surveys, and further research could use household panel data to measure changes in farmer behavior over time and refine the resilience framework.

Competing interest declaration

The authors declare no competing interests.

CRediT authorship contribution statement

Zhiping Duan: Writing – original draft, Investigation, Data curation, Conceptualization. **Jinghan Li:** Writing – original draft, Methodology, Formal analysis. **Fan Li:** Writing – original draft, Conceptualization. **Jiping Ding:** Writing – review & editing, Methodology, Funding acquisition. **Yuanmao Jiang:** Writing – review & editing. **Jianguo Liu:** Writing – review & editing. **Weifeng Zhang:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

We thank all farmers and county government staff who supported the study. This work was financially supported by the National Key Technologies R&D Program of China (grant no. 2016YFD0201303), the National Natural Science Foundation of China (72003148), the Fundamental Research Funds for the Central Universities of Huazhong Agricultural University (grant no. 2662022ZKQD002), and the Construction of Agricultural Carbon Neutrality Account in Quzhou City, Zhejiang Province.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.140303.

References

Acevedo, M., Pixley, K., Zinyengere, N., Meng, S., Porciello, J., 2020. A scoping review of adoption of climate-resilient crops by small-scale producers in low- and middle-income countries. Nat. Plants 6, 1231–1241. https://doi.org/10.1038/s41477-020-00783-z.

Ali, S., Liu, Y., Nazir, A., Ishaq, M., Shalmani, A., 2021. Rural farmers perception and coping strategies towards climate change and their determinants: evidence from khyber pakhtunkhwa province, Pakistan. J. Clean. Prod. 291 https://doi.org/10.1016/j.jclepro.2020.125250.

Anconelli, S., Facini, O., Marletto, V., Pitacco, A., Rossi, F., Zinoni, F., 2002. Micrometeorological test of microsprinklers for frost protection of fruit orchards in Northern Italy. Phys. Chem. Earth 27, 1103–1107. https://doi.org/10.1016/s1474-7065(02)00146-8.

Anderson, R., Bayer, P.E., Edwards, D., 2020. Climate change and the need for agricultural adaptation. Curr. Opin. Plant Biol. 56, 197–202. https://doi.org/10.1016/j.pbi.2019.12.006.

Autio, A., Johansson, T., Motaroki, L., Minoia, P., Pellikka, P., 2021. Constraints for adopting climate-smart agricultural practices among smallholder farmers in Southeast Kenya. Agric. Syst. 194 https://doi.org/10.1016/j.agsy.2021.103284.

Bizikova, L., et al., 2020. A scoping review of the contributions of farmers' organizations to smallholder agriculture. Nature Food 1, 620–630. https://doi.org/10.1038/s43016-020-00164-x.

Blekking, J., Gatti, N., Waldman, K., Evans, T., Baylis, K., 2021. The benefits and limitations of agricultural input cooperatives in Zambia. World Dev. 146, 105616 https://doi.org/10.1016/j.worlddev.2021.105616.

Buadi, D.K., Anaman, K.A., Kwarteng, J.A., 2013. Farmers' perceptions of the quality of extension services provided by non-governmental organisations in two municipalities in the Central Region of Ghana. Agr syst 120, 20–26. https://doi.org/10.1016/j.agsy.2013.05.002.

Carter, C., Krissoff, B., Zwane, A.P., 2006. Can country-of-origin labeling succeed as a marketing tool for produce? Lessons from three case studies. Can. J. Agric. Econ. 26, 513–530. https://doi.org/10.1111/j.1744-7976.2006.00064.x.

Chen, A., Huang, L., Liu, Q., Piao, S., 2021. Optimal temperature of vegetation productivity and its linkage with climate and elevation on the Tibetan Plateau. Global Change Biol. 27, 1942–1951. https://doi.org/10.1111/gcb.15542.

Chen, L., et al., 2018. Spring phenology at different altitudes is becoming more uniform under global warming in Europe. Global Change Biol. 24, 3969–3975. https://doi.org/10.1111/gcb.14288.

Choquette-Levy, N., Wildemeersch, M., Oppenheimer, M., Levin, S.A., 2021. Risk transfer policies and climate-induced immobility among smallholder farmers. Nat. Clim. Change 11, 1046–1054. https://doi.org/10.1038/s41558-021-01205-4.

China Meteorological Administration (CMA), 2014. China Meteorological Disaster Yearbook 2013. Meteorological Press, Beijing (in Chinese).

Cottrell, R.S., et al., 2019. Food production shocks across land and sea. Nat. Sustain. 2, 130–137. https://doi.org/10.1038/s41893-018-0210-1.

Crowther, J., Zimmer, H., Thi, H.L., Quang, T.L., Nichols, J.D., 2020. Forestry in vietnam: the potential role for native timber species. For. Pol. Econ. 116, 102182 https://doi.org/10.1016/j.forpol.2020.102182.

Dalhaus, T., Schlenker, W., Blanke, M.M., Bravin, E., Finger, R., 2020. The effects of extreme weather on apple quality. Sci. Rep. 10, 7919. https://doi.org/10.1038/s41598-020-64806-7.

Davis, K.F., Downs, S., Gephart, J.A., 2020. Towards food supply chain resilience to environmental shocks. Nature Food 2, 54–65. https://doi.org/10.1038/s43016-020-00196-3.

Dang, H.L., Li, E., Nuberg, I., Bruwer, J., 2019. Factors influencing the adaptation of farmers in response to climate change: a review. Clim. Dev. 11, 765–774. https://doi.org/10.1080/17565529.2018.1562866.

Delgado, A., Dapena, E., Fernandez, E., Luedeling, E., 2021. Climatic requirements during dormancy in apple trees from northwestern Spain – global warming may threaten the cultivation of high-chill cultivars. Eur. J. Agron. 130, 126374 https://doi.org/10.1016/j.eja.2021.126374.

Duan, N., et al., 2017. Genome re-sequencing reveals the history of apple and supports a two-stage model for fruit enlargement. Nat. Commun. 8, 249. https://doi.org/10.1038/s41467-017-00336-7.

Duan, Z.P., Ding, J.P., Jiang, Y.M., Zhang, W.F., 2023. Integrated soil-fruit-climate management system to improve apple production stability. Sci. Total Environ. 905, 167840 https://doi.org/10.1016/j.scitotenv.2023.167840.

Esfandiari, M., Mirzaei Khalilabad, H.R., Boshrabadi, H.M., Mehrjerdi, M.R.Z., 2020. Factors influencing the use of adaptation strategies to climate change in paddy lands of Kamfiruz, Iran. Land Use Pol. 95 https://doi.org/10.1016/j.landusepol.2020.104628.

Fanzo, J., Davis, C., McLaren, R., Choufani, J., 2018. The effect of climate change across food systems: implications for nutrition outcomes. Global Food Secur. 18, 12–19. https://doi.org/10.1016/j.gfs.2018.06.001.

FAO (Food and Agriculture Organization), 2013. https://www.fao.org/home/zh/.

FAO (Food and Agriculture Organization). Online statistical database: Crop. FAOSTAT. http://www.fao.org/faostat/en/#data Accessed February 5, 2023.

Frank, K.A., et al., 2015. Increasing information usability for climate adaptation: the role of knowledge networks and communities of practice. Global Environ. Change 32, 30–39. https://doi.org/10.1016/j.gloenvcha.2015.02.007.

Fujisawa, M., Kobayashi, K., 2010. Apple (malus pumila var. domestica) phenology is advancing due to rising air temperature in northern Japan. Global Change Biol. 16, 2651–2660. https://doi.org/10.1111/j.1365-2486.2009.02126.x.

Gezahegn, T.W., Passel, S.V., Berhanu, T., D'Haese, M., Maertens, M., 2019. Big is efficient: evidence from agricultural cooperatives in Ethiopia. Agric. Econ. 50 (5), 555–566. https://doi.org/10.1111/agec.12509.

Google Satelliet Map. https://earth.google.com/. (Accessed 20 August 2022).

Greg, L., 2014. Understanding the nested, multi-scale, spatial and hierarchical nature of future climate change adaptation decision making in agricultural regions: a narrative literature review. J. Rural Stud. 37, 38–49. https://doi.org/10.1016/j.jrurstud.2014.10.004.

Haigh, T., Koundinya, V., Hart, C., Klink, J., Lemos, M., Mase, A.S., Prokopy, L., Singh, A., Todey, D., Widhalm, M., 2018. Provision of climate services for agriculture: public and private pathways to farm decision-making. Bull. Am. Meteorol. Soc. 99 (9), 1781–1790. https://doi.org/10.1175/BAMS-D-17-0253.1.

Harjanne, A., 2017. Servitizing climate science—institutional analysis of climate services discourse and its implications. Global Environ. Change 46, 1–16. https://doi.org/10.1016/j.gloenvcha.2017.06.008.

Hasegawa, T., et al., 2021. Extreme climate events increase risk of global food insecurity and adaptation needs. Nature Food 2, 587–595.

Hausman, J.K., Rhode, R.W., Wieland, J.F., 2021. Farm product prices, redistribution, and the early U.S. Great depression. J. Econ. Hist. 81 (3) https://doi.org/10.1017/s0022050721000334.

He, X.J., Yan, J.Z., Yang, L.E., Wu, Y., Zhou, H., 2022. Climate change adaptation of smallholders on the Tibetan plateau under government interventions. J. Clean. Prod. 381, 135171 https://doi.org/10.1016/j.jclepro.2022.135171.

Hong, C., Mueller, N.D., Burney, J.A., Zhang, Y., Davis, S.J., 2020. Impacts of ozone and climate change on yields of perennial crops in California. Nature Food 1. https://doi.org/10.1038/s43016-020-0043-8.

Huo, X., et al., 2022. China apple industry development report 2020. China Fruit Vegetable 42. https://doi.org/10.19590/j.cnki.1008-1038.2022.02.001 (in Chinese).

Imai, K., Keele, L., Tingley, D., et al., 2011. Unpacking the black box of causality: learning about causal mechanisms from experimental and observational studies. Am. Polit. Sci. Rev. 105 (4), 765–789. https://doi.org/10.1017/s0003055411000414.

Israeli, O., 2006. A Shapley-based decomposition of the R-Square of a linear regression. J. Econ. Inequal. 5, 199–212. https://doi.org/10.1007/s10888-006-9036-6.

Janik, E. Apple, 2011. A Global History. Reaktion Books. The University of Chicago Press.

Jeffrey Price, T., et al., 2005. Practices choice under changing peanut policies. Agric. Econ. 33, 11–19.

Jiang, Y., et al., 2018. Multi-objective economic-resource-production optimization of sustainable organic mixed farming systems with nutrient recycling. J. Clean. Prod. 196, 304–330. https://doi.org/10.1016/j.jclepro.2018.06.040.

Khanal, U., Wilson, C., 2019. Derivation of a climate change adaptation index and assessing determinants and barriers to adaptation among farming households in Nepal. Environ. Sci. Pol. 101, 156–165. https://doi.org/10.1016/j.envsci.2019.08.006.

Khanal, U., Wilson, C., Lee, B., Hoang, V.-N., 2017. Smallholder farmers' participation in climate change adaptation programmes: understanding preferences in Nepal. Clim. Pol. 18, 916–927. https://doi.org/10.1080/14693062.2017.1389688.

Kumasi, T.C., Antwi-Agyei, P., Obiri-Danso, K., 2019. Small-holder farmers' climate change adaptation practices in the Upper East Region of Ghana. Environ. Dev. Sustain. 21, 745–762. https://doi.org/10.1007/s10668-017-0062-2.

Lei, Y., et al., 2018. 5 Freeze injuries effect on apple during flowering period in Yan'an. Chinese Agricultural Science Bulletin 34, 102–107 (in Chinese).

Li, H., et al., 2009. Effect of grass planting on the microclimate of apple orchard in the dryland area of Loess Plateau. Acta Agrestia Sinica 17 (in Chinese).

Luning, P.A., Marcelis, W.J., 2007. A conceptual model of food quality management functions based on a techno-managerial approach. Trends Food Sci. Technol. 18 (3), 159–166. https://doi.org/10.1016/j.tifs.2006.10.021.

Mangnus, E., Schoonhoven-Speijer, M., 2020. Navigating dynamic contexts: african cooperatives as institutional bricoleurs. Int. J. Agric. Sustain. 18 (2), 99–112. https://doi.org/10.1080/14735903.2020.1718991.

Mehrabi, Z., 2019. Food system collapse. Nat. Clim. Change 10, 16–17. https://doi.org/10.1038/s41558-019-0643-1.

Milošević, T., Milošević, N., Mladenović, J., 2022. The influence of organic, organo-mineral and mineral fertilizers on tree growth, yielding, fruit quality and leaf nutrient composition of apple cv. 'Golden Delicious Reinders'. Sci. Hortic. (Canterb.) 297, 110978. https://doi.org/10.1016/j.scienta.2022.110978.

Ministry of Agriculture and Rural Affairs of the People's Republic of China, 2003. Apple Advantageous Regional Development Plan. http://www.moa.gov.cn/xw/zwdt/200305/t20030526_86294.htm.

Moat, J., et al., 2017. Resilience potential of the Ethiopian coffee sector under climate change. Nat. Plants 3, 110.1038/nplants.2017.81.

Mohanty, M.K., Thakurta, P.K.G., Kar, S., 2023. Agricultural commodity price prediction model: a machine learning framework. Neural Comput. Appl. 35, 15109–15128. https://doi.org/10.1007/s00521-023-08528-7.

Morgan, S.L., Winship, C., 2015. Counterfactuals and Causal Inference: Methods and Principles for Social Research. Cambridge University Press, Cambridge, UK.

Nguyen, T., Jolly, C.M., 2020. Diverse cooperative field membership and small-scale producers' access to certification. Rev Fish Sci Aquac 152, 228–246. https://doi.org/10.1080/23308249.2019.1701984.

Ojo, T.O., Baiyegunhi, L.J.S., 2021. Climate change perception and its impact on net farm income of smallholder rice farmers in South-West, Nigeria. J. Clean. Prod. 310 https://doi.org/10.1016/j.jclepro.2021.127373.

Oyenihi, A.B., Belay, Z.A., Mditshwa, A., Caled, O.J., 2022. "An apple a day keeps the doctor away": the potentials of apple bioactive constituents for chronic disease prevention. J. Food Sci. 87, 2291–2309. https://doi.org/10.1111/1750-3841.16155.

Parkes, H., Darbyshire, R., White, N., 2020. Chilling requirements of apple cultivars grown in mild Australian winter conditions. Sci. Hortic. (Canterb.) 260, 108858. https://doi.org/10.1016/j.scienta.2019.108858.

Pfleiderer, P., Menke, I., Schleussner, C.F., 2019. Increasing risks of apple tree frost damage under climate change. Climatic Change 157, 515–525. https://doi.org/10.1007/s10584-019-02570-y.

Ray, D.K., Gerber, J.S., MacDonald, G.K., West, P.C., 2015. Climate variation explains a third of global crop yield variability. Nat. Commun. 6, 5989. https://doi.org/10.1038/ncomms6989.

Ray, S., Lama, A., Mishra, P., Biswas, T., Sankar Das, S., Gurung, B., 2023. An ARIMA-LSTM model for predicting volatile agricultural price series with random forest technique. Appl. Soft Comput. 149, 110939 https://doi.org/10.1016/j.asoc.2023.110939.

Ribeiro, A.C., De Melo-Abreu, J.P., Snyder, R.L., 2006. Apple orchard frost protection with wind machine operation. Agric. For. Meteorol. 141, 71–81. https://doi.org/10.1016/j.agrformet.2006.08.019.

Rodrigo, J., 2000. Spring frosts in deciduous fruit trees – morphological damage and flower hardiness. Sci. Hortic. (Canterb.) 85, 155–173. https://doi.org/10.1016/s0304-4238(99)00150-8.

Soglo, Y.Y., Nonvide, G.M.A., 2019. Climate change perceptions and responsive strategies in Benin: the case of maize farmers. Clim. Change 155, 245–256. https://doi.org/10.1007/s10584-019-02452-3.

Tanaka, A., et al., 2015. Adaptation pathways of global wheat production: importance of strategic adaptation to climate change. Sci. Rep. 5, 14312 https://doi.org/10.1038/srep14312.

Unterberger, C., Brunner, L., Nabernegg, S., Steininger, K.W., Steiner, A.K., Stabentheiner, E., Monschein, S., Truhetz, H., 2018. Spring frost risk for regional apple production under a warmer climate. PLoS One 13 (7), e0200201. https://doi.org/10.1371/journal.pone.0200201.

Vincent, K., et al., 2013. Farmers' responses to climate variability and change in southern Africa – is it coping or adaptation? Clim. Dev. 5, 194–205. https://doi.org/10.1080/17565529.2013.821052.

Vincent, K., et al., 2020. Re-balancing climate services to inform climate-resilient planning – a conceptual framework and illustrations from sub-Saharan Africa. Clim Risk Manag 29. https://doi.org/10.1016/j.crm.2020.100242.

Wang, J., et al., 2015. Study on freezing index and weather conditions causing Shaanxi apple fluorescence freezing injury in 2013. J. Fruit Sci. 32, 100–107. https://doi.org/10.13925/j.cnki.gsxb.20140256 (in Chinese).

Wen, Z.L., Ye, B.J., 2014. Analyses of Mediating Effects: the development of methods and models. Adv. Psychol. Sci. 22, 731–745 (in Chinese).

WFP (World Food Programme), 2016. Connecting smallholder farmers to markets. http://documents.wfp.org/stellent/groups/public/documents/communications/wfp277969.pdf.

Wijk, M.T.V., Merbold, L., Hammond, J., Butterbach-Bahl, K., 2020. Improving assessments of the three pillars of climate smart agriculture: current achievements and ideas for the future. Front. Sustain. Food Syst. 4 https://doi.org/10.3389/fsufs.2020.558483.

Ye, D., Ng, Y.K., Lian, Y., 2015. Culture and happiness. Soc. Indicat. Res. 123, 519–547. https://doi.org/10.1007/s11205-014-0747-y.

Zaller, J.G., Oswald, A., Wildenberg, M., Burtscher-Schaden, H., Nadeem, I., Formayer, H., Paredes, D., 2023. Potential to reduce pesticides in intensive apple production through management practices could be challenged by climatic extremes. Sci. Total Environ. 872, 162237 https://doi.org/10.1016/j.scitotenv.2023.162237.

Zhang, S.Y., Xie, X.X., Luo, Y., Liu, X.Q., Zhao, M.J., 2023. The influence of asset specificity on farmers' willingness to participate in fallow from the perspective of farmer differentiation. Front. Environ. Sci. 11 https://doi.org/10.3389/fenvs.2023.1107545.

Zhang, W.F., et al., 2016. Closing yield gaps in China by empowering smallholder farmers. Nature 537, 671–674. https://doi.org/10.1038/nature19368.

Zhang, Q.Q., 2021. The Evolution and Advantage Evaluation of Apple Production Layout in China. Northwest A&F University.

Zhu, Z., et al., 2018. Life cycle assessment of conventional and organic apple production systems in China. J. Clean. Prod. 201, 156–168. https://doi.org/10.1016/j.jclepro.2018.08.032.