Effects of extreme temperature on China’s tea production

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Abstract

The production of tea (Camellia sinensis (L.) Kuntze), the world’s second most consumed beverage, is susceptible to extreme weather events. However, our understanding about the impacts of extreme temperatures and climate change on tea yields remains fairly limited. Here we quantify the historical and predict future fluctuations in tea yield caused by extreme temperatures in China, the largest tea producing country. We found that both heat and cold extremes were associated with significantly reduced tea yields. In the present climate, dominating cold extremes influence more than half of China’s tea production, with a maximum of 56.3% reduced annual production. In the near future, we predict positive net impacts of climate change on tea yield in all study regions at both the 1.5 °C and 2.0 °C global warming levels. Climate warming may diminish the negative impacts of cold extremes to 14%, especially at the current most affected northern tea growing regions (∼28° N). However, new areas of yield reduction by intensified heat extremes will emerge, up to 14%–26% yield losses estimated at the Yangtze River (∼30° N) and southern China (<∼25° N) regions. Although the Paris Agreement targets limiting global warming to 1.5 °C, we expect up to 11%–24% heat-induced yield loss in Chongqing, Hunan, Anhui, and Zhejiang. Increasing heat extremes pose the most challenging changes for tea production in China. Therefore, addressing the regional difference of extreme temperature shifts is urgent for adapting tea production to climate change.

1. Introduction

Changes in climate have caused substantial yield losses for several major staple crops, including wheat, rice, maize, soybean, and cotton [1–5]. Recent studies have also highlighted the vulnerability of ‘luxury’ goods to climate change, including the popular beverages of wine [6], coffee [7], and beer [8]. However, our understanding about the impacts of climate change on tea (Camellia sinensis (L.) Kuntze) production remains fairly limited, with relatively few studies on the subject [9–11].

Tea is the second most consumed beverage in the world [9, 10, 12] and global consumption was nearly 5 million tonnes in 2013 [13]. It is one of the most important cash crops in developing countries, and as a result tea cultivation is of considerable socio-economic importance for rural development and poverty alleviation [14]. China is the largest tea producing country in the world (2.41 million tonnes) (figure 1(A)), followed by India (1.25 million tonnes) and Kenya (0.47 million tonnes) [15]. Tea is an economically valuable and symbolic cultural commodity in both traditional and modern China.
80 million people are involved in the tea industry across China, and it is a major source of income for smallholder farmers, especially in the major tea growing regions of southern China [9, 14, 16]. In China, farmers usually pluck newly emerged tea leaves and buds several times from early spring (early before Qingming Festival) to late autumn [17], such as in the renowned green tea production region Zhejiang province [18]. Based on how the leaves are processed after harvesting, tea beverages can be classified as white, green, black, yellow, dark, and wulong [19, 20]. The postprocessing decision is mainly related to the local tea cultivars, cultures, traditions, and economic factors.

Despite the vital importance of tea in China, research efforts to understand the impacts of climate change on tea production are considerably limited. Unfavorable weather conditions can be detrimental to tea crop production and substantially reduce yields and quality [11, 21–25]. Tea yield has declined as the climate has warmed in India, especially when the monthly temperature exceeds ∼27 °C [21]. In Sri Lanka, a monthly mean temperature higher than 22 °C is thought to reduce tea productivity [22]. In China, monsoon dynamics affected harvest timing decisions and reduced tea productivity by ∼0.5% for a 1% increase in the monsoon season retreat date [9]. In southwest and east China, tea quality deteriorated due to rising temperatures and drought events [11, 24, 25]. Furthermore, heat extremes where the daily maximum temperature reaches 35 °C or higher have increased and are projected to be longer and more frequent in China [26], which potentially threaten tea production and the livelihoods of tea dependent growers. Although most previous research has emphasized the importance of heat stress, cold stress also has the potential to reduce tea yield because it usually occurs during the early growing season when the tea bud emerges and may limit the number of harvests in a given year [27]. Cold stress results in both physiological and structural damages to tea leaves. Physiologically, cold stress reduces enzyme activity, photosynthesis rate and causes water loss, imbalance metabolism. Structurally, cold stress can destruct the membrane system, form intracellular ice, and deform tea leaves [28]. However, the quantitative influences of the full range of temperatures on tea productivity remain unclear. Further, it is unclear how tea yields specifically respond to temperature extremes, which will be altered via climate warming. We hypothesize that the rainfed cultivation system used for tea production [16] is highly likely to be susceptible to the challenges posed by climate change, especially with regards to temperature extremes.

Here we quantified the effects of temperature extremes on tea yield and demonstrated the historical and future effects of temperature extremes on tea yields over the long-term and at nearly national scale. We collected a new long-term (1990–2016) fine-resolution, prefecture-scale tea production dataset and merged it with weather data; this panel dataset covers most of the tea growing regions in China (figure 1B). Then we developed a regression model approach to analyze the nonlinear responses of tea yield to historical weather variability. A total of 21 global climate models (GCMs) were used to estimate future temperature extremes and their consequent impacts on tea yields under the 1.5 °C and 2.0 °C warming scenarios.

2. Methods and materials

2.1. Study area

The major tea growing regions in mainland China are around 20°–37° N, 98°–121° E [9]. After considering data availability and quality, we selected 41 prefectoral cities and 1 municipality as our study areas (figure 1B). The area investigated represented around 70% of national tea production in 2016. The 41 prefectoral cities include variable climate conditions and are distributed across 14 provinces: Anhui (AH), Fujian (FJ), Guangdong (GD), Guangxi (GX), Guizhou (GZ), Hubei (HB), Henan (HeN), Hunan (HuN), Jiangxi (JX), Sichuan (SC), Shandong (SD), Shaanxi (SX), Yunnan (YN) and Zhejiang (ZJ).

2.2. Tea yield and cultivation area data

We collected the tea production data for the years 1990–2016. Annual tea production and its cultivation area are compiled by the Chinese Bureau of Statistics, in the statistical yearbook, or separately in the yearbook for each prefecture. This study focuses on the primary tea yield rather than various processed tea products. We use the cultivated area to compute annual tea yields (t ha⁻¹). We observed that there was rapid expansion in the cultivated area for some years in few cities. Tea plantations are not usually harvested for the first two years after they have been planted, so rapid expansion could bias the calculation of tea yields when using cultivated area in the calculation. In these cases, we used the area data before the rapid expansion to compute tea productivity. In addition, we collected soil type data from the China Soil Database (http://vdb3.soil.csdb.cn/) (supplementary table 1 (available online at stacks.iop.org/ERL/16/044040/mmedia)). Cultivar information was obtained from the statistic yearbook including three major categories: arbor, semi-arbor, and shrub type (supplementary table 1).

2.3. Weather observation dataset

Daily gridded maximum and minimum surface air temperature and precipitation data with a spatial resolution of a half degree in latitude and longitude were accessed from the China Meteorological Administration (http://data.cma.cn/). The dataset is a reanalyzed product that has been analyzed by the

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thin plate spline interpolation method in conjunction with the Global 30 Arc-Second Elevation model. The weather data quality is controlled by a cross-validation method and error analysis. To avoid urban areas and better represent tea plantations, we further chose the gridded weather data which located at tea growing areas in each city according to the tea distribution map from China Tea Yearbook published in 2011.

2.4. Regression model
Process-based crop growth models are useful and effective tools to investigate the impacts of climate on crop productivity. However, contemporary crop models still have limited capacity and high uncertainties to account for extreme climate events, particularly for cold and heat waves [29–31]. Besides, process-based crop growth models usually require intensive data inputs to calibrate model parameters, which is usually unavailable across large study areas and through long periods. In contrast, previous studies have shown the usefulness of data-driven statistical models to quantify the effects of irrigation, heat stress, or climate change on crop yields [3, 32–34]. Although the weakness of the statistical approach (e.g. non-mechanistic) is also well known, statistical models trained with long-term and multiple site data show considerable performance and require limited field calibration when applying to broad-scale [34]. Therefore, in this study, we constructed a statistical panel model with long-term (1990–2016) 42 cities tea production data to analyze the relationship between annual tea productivity and exposure for different temperature intervals at the resolution of the prefecture scale (equations (1) and (2)).

Climate conditions strongly affect the tea crop (Camellia sinensis (L.) Kuntze) growth, yield, and quality [27]. Previous literature has identified an ideal temperature range for tea crop growth between 10°C and 30°C with 1500–2000 mm annual precipitation [27]. A tea crop can usually tolerate a maximum temperature of 35°C, but several days under such conditions will lead tea leaves to wilt and fall [13, 27]. The growing seasons for tea cultivation, vary considerably with the local climate. In this study, we considered local farming practices and examined monthly mean temperature across 1981–2010 to determine months with average temperature >10°C; these months, March–October, were defined as the growing season. Temperature effects on yield were assumed to be cumulative over the growing season [3]. We applied this assumption and computed the time distribution of the crop was exposed to a certain temperature interval with 2°C step. The temperature boundaries investigated are 0°C to 36°C, since daily mean temperature (T\text{mean}) never exceeded 36°C or hardly below 0°C across the study area during 1990–2016.

\[ T_{k,p,i} = \sum_{j=1}^{N} \text{Day}_{k,p,j} \]

where \( T_{k,p,i} \) is the accumulated temperature exposure in days to a given temperature bin \( k \) in each city \( p \) and
year $i$ through the growing season, $N$ is the number of the growing days, $j$ is the time step as one day.

Subsequently, we constructed a commonly applied statistical model as follows:

$$Y_{p,i} = \sum_{k=1}^{18} \beta_k T_{k,p,i} + \delta Z_{p,i} + \gamma Z_{p,i}^2 + \tau_i + \mu_p + \varepsilon$$

where $Y_{p,i}$ is the natural logarithmic yield for prefecture $p$ in year $i$, $Z_{p,i}$ is the growing season precipitation for each city and year, which is controlled for using a quadratic relationship for its potential nonlinear effects. In contrast, we constructed 18 temperature bins instead of its quadratic term which is illustrated in equation (1). To show the impacts of changing the bin number and temperature step, we also performed the regression analysis using 36 bins with 1-degree step. Impacts of different temperature exposure counting methods were also tested, namely in day (equation (1)) [3] or in degree [1]. Although soil moisture also affects tea plant growth [27], it is still challenging to include in the regression model due to the short of long-term and high spatial-temporal resolution of the root zone soil moisture database. Therefore, we consider temperature and precipitation as the predominant yield affecting climate factors which have been extensively demonstrated by previous studies for other crops [3, 32–34] and also for the tea plant [21, 22, 35]. Yearly fixed effects ($\tau_i$) control for nonlinear changes in tea yields over time induced by changes in agronomic technology or economic shocks. Prefecture fixed effects ($\mu_p$) control for time-invariant factors that differ between locations, including soil type and cultivars (supplementary table 1). To handle the potential collinearity issue, we conducted the variance inflation factor (VIF) analysis. We considered VIFs between 1 and 5 is the reasonable range to warrant corrective measures [36]. We used the Python and R programming languages with Numpy, pandas, matplotlib, ggplot2, and statsmodels for data preparation, visualization, and regression analysis. To avoid overfitting and to verify the robustness of the proposed yield model (equation (2)), we randomly divided all the samples as 80% for training and 20% for validation. To prevent potentially biased sample split, we have repeated the process six times.

### 2.5. Estimation of future climate change impacts on tea yields

We applied the regression model (equation (3)) which is derived from equation (2) to compute tea yield change associated with future climate change.

$$\Delta \text{Yield} = \sum_{k=1}^{18} \beta_k \Delta T_{k,p,i} + \delta \Delta Z + \gamma \Delta Z^2$$

where $\Delta \text{Yield}$ is the change of log yield. $\beta_k, \delta$ and $\gamma$ are the coefficients derived from equation (2). $\Delta T_{k,p,i}$ is the change of temperature exposure at each temperature bin and at each spatial grid during the growing season with one day time step. $\Delta Z$ is the change of water availability, which is defined as accumulated monthly precipitation within growing season. In addition, we computed the yield change (%) due to cold/heat extremes (stress) as well as change in water availability. Here, cold and heat extremes (stress) are defined as $0 \, ^\circ\text{C} < T_{\text{mean}} < 4 \, ^\circ\text{C}$ and $34 \, ^\circ\text{C} < T_{\text{mean}} \leq 36 \, ^\circ\text{C}$, respectively. The independent cold/heat stress or water availability driven yield change was estimated with the corresponding coefficient. The analysis we undertook assumed that there was no adaptation.

The projected daily and monthly mean surface air temperature (TAS), as well as monthly precipitation (P) from the 21 GCMs that were used in the 5th phase of Coupled Model Intercomparison Project for the historical period 1986–2005 and the RCP8.5 scenario for 2006–2100, were obtained (supplementary table 2) [37, 38]. These were spatially interpolated onto $0.5^\circ \times 0.5^\circ$ horizontal grids for latitude and longitude, respectively, using the statistical method [34, 35].

We then project the change in heat and cold extreme, water availability and respective change in annual tea yield over the analysis domain when the global mean temperature reaches 1.5 $^\circ\text{C}$ and 2 $^\circ\text{C}$ above the pre-industrial level. At first, we computed the accumulated temperature exposure to individual temperature bins and respective heat and cold stress using daily mean TAS as well as water availability using monthly $P$ and then calculated annual tea yield following equation (2) for the whole period 1986–2100. The change in the exposure to individual temperature bins including heat and cold extreme and water availability for 2006–2100 is computed as anomalies of 20 year-equal-weighted running average based on 1986–2005 climatology, thereby change in annual tea yield for 2006–2100 follows equation (3). In addition, we computed yield change driven by change in heat and cold extreme, and water availability for 2006–2100. Next, we estimated the time when the increase in global mean temperature was expected to reach 1.5 $^\circ\text{C}$ and 2 $^\circ\text{C}$ relative to the pre-industrial period, denoted by $t_{1.5}$ and $t_2$, respectively, using monthly mean TAS. The $t_{1.5}$ and $t_2$ are determined when the change in 20 year running mean of global mean temperature firstly reaches 0.9 $^\circ\text{C}$ and 1.4 $^\circ\text{C}$ above the climatology of 1986–2005, respectively (supplementary table 3), assuming that the base period 1986–2005 was warmer than the pre-industrial level by at least 0.6 $^\circ\text{C}$ [39]. For all projected variables, each 20 year period is indexed by its final year. For example, the 20 year running average for 2040 indicates the average for 2021–2040. Thus, we can finally calculate the change in heat and cold extreme, water availability, and respective change in tea yield under the 1.5 $^\circ\text{C}$
and 2 °C warming levels for all individual GCMs. The ensemble mean, 84th and 16th percentile value, and the 16%–84% range of future projections are calculated using the whole ensemble of model projections across the 21 GCMs. The 16%–84% range (± one standard deviation) indicates the uncertainty range of projections and is computed as the difference between the 84th and 16th percentile values.

3. Results

3.1. Susceptibility to cold and heat extremes

Figure 2 shows the nonlinear temperature (daily mean) effects on tea yield variations and the mean heat exposure at each temperature bin. The effects of soil type and cultivar in each prefecture were controlled in our model via prefecture fixed effects, as was technology improvement over time (equation (2)). Through the validation, we found that the model could reasonably well estimate the tea yield based on the variables we constructed (supplementary figure 1). Sensitivity results of changing the number of temperature bins are available in supplementary figure 2. Sensitivity results of different temperature exposure counting methods are available in supplementary figure 3. We found considerably larger model confidence interval width compared to equation (2).

We found that both heat and cold extremes were associated with significantly reduced tea yields ($P < 0.05$), while a wide range of intermediate temperatures exhibited minor yield impacts. We transformed the yield to logarithmic form. Therefore, the cold stress coefficient of $-0.04$ (or $-0.02$) indicates that the temperature of each day between 0 and 2 (or 2–4) °C reduces the tea yield by 4% (or 2%). Therefore, each day the tea crop was exposed to extreme cold ($0 ^\circ C < T_{\text{mean}} \leq 4 ^\circ C$) decreases yield around 2%–4% compared to non-stress conditions, translating into around 46 833–93 667 t (2%–4%) loss based on national production in 2016. Each day of extreme heat ($34 ^\circ C < T_{\text{mean}} \leq 36 ^\circ C$) decreases yields around 3.7%, translating to around 86 642 t of tea production in 2016. Tea production across China shows great susceptibility to both cold and heat extremes. Besides, we found non-significant effects of the growing season precipitation on the yield, indicating that current tea production in China is likely dominated by the temperature. Detailed results of the regression analysis are available in supplementary table 4. The number of samples affected by the cold or heat extreme is available in supplementary figure 4.

3.2. Substantial cold extremes-induced yield loss

After confirming the quantitative relationship between tea yield and temperature extremes, we quantified the effects of historical extreme temperatures on tea yield losses by the regression model. Extreme cold stress occurred in several major tea growing regions up to 18 d yr$^{-1}$ (figure 3(A)). The majority of the production area was affected,
including provinces in the northern, central, and eastern regions of China. These were Shandong (SD), Shaanxi (SX), Henan (HeN), Hubei (HB), Sichuan (SC), Guizhou (GZ), Hunan (HuN), Jiangxi (JX), Fujian (FJ), Anhui (AH) and Zhejiang (ZJ). Impacts of extreme cold stress are shown by the historical maximum yield loss values for the study period. These values are shown as both a percentage (figure 3(C)) and as actual values (figure 3(E)). The yield loss maximum ranged from 0% to 56.3% (figure 3(C)). Losses were particularly high in in Rizhao (56.3%, in SD), Hanzhong (45.1%, in SX), and Yichang (47.3%, in HB), and were considerable in Xinyang (28.6%, in HeN). Furthermore, in the top tea producing province, Fujian, there were considerable tea yields losses in Ningde (33.1%) and Nanping (11.4%). Losses were around 4% in the two other prefectures in Fujian. We also present the spatial-temporal distribution of the cold stress-induced yield losses, which shows distinctive regional characteristics and interannual variability (figure 4). Between 1990 and 2016, only tea production in Chongqing (CQ) and Guangdong (GD) were not affected by cold stress. Together, they represent just 5% of national production. Regions above 25° N are more likely to suffer from more severe cold stress with a maximum yield reduction of 56.3% recorded in Shandong (SD) province.

Heat stress also has a strong negative impact on tea yield, but has historically occurred over a smaller area than cold stress. Intensive heat stress only occurred in the southwestern (CQ) region and parts of the central (HB) and eastern (AH, ZJ) regions, where exposure occurred from 0.8 to 5.2 d yr⁻¹ (figure 3(B)). Heat stress events occurred in the Yangtze River regions (near to 30° N) and the heat-induced maximum yield losses were also high in Chongqing (20.4%), Huzhou (11.1%, in ZJ), and
Figure 4. Spatial-temporal distribution of the historical cold stress-induced yield losses. Each box illustrates the distribution of losses due to cold stress for each city across time (1990–2016). The province sequence (x-axis) is based on production levels.

Xuanchen (4.8%, in AH) (figure 3(D)). However, yield losses due to extreme heat were less than those caused by cold damage.

3.3. Alleviated cold stress but intensified heat stress

Estimating impacts of future climate change on tea yield is important when planning and implementing adaptation and mitigation policies. We applied the regression model (equation (3)) to predict the tea yield changes by considering changes in growing season temperature and precipitation associated with the two temperature goals of the Paris Agreement 2015: 1.5 °C and 2.0 °C above the pre-industrial level. We produced these estimations under the Representative Concentration Pathway (RCP) 8.5 scenario. The uncertainty of the estimation is presented as the 16%–84% range (+/- one standard deviation) of individual projections including accumulated cold and heat stress and water availability as well as relevant changes in tea yield (supplementary figures 5 and 6).

Cold stress is expected to fall, but heat stress is predicted to intensify in the near future over almost all the tea production regions at both the 1.5 °C and 2.0 °C warming levels (supplementary figures 7 and 8). Compared to the present climate, the alleviation of cold stress is most pronounced (up to 3 d) in northern tea growing regions (>28° N), whereas the increase in heat stress is notable (1.0–2.5 d) in southern China (<∼25° N) (supplementary figures 7 and 8).

Unexpectedly, we find positive net impacts of all the climate indices on yield in all study regions by up to 14% (supplementary figures 7(D) and 8(D)). Regions above 28° N, which produce ~48% of national tea yield, will experience potential yield increase mostly due to decrease in cold stress (figures 5(A) and (B)). Yields in these regions are estimated to increase by around 2%–10% under 1.5 °C warming compared to the present climate.

Conversely, a considerable intensification of heat stress will partially offset the beneficial effects of the reduced cold stress. In the regions of southern China (<∼25° N) intensified heat stress could reduce tea production by extra 1.5%–10% compared to present climate (figure 5). Parts of the Yangtze River regions (nearly 30° N) are also expected to suffer amplified heat-induced yield loss (extra 2%–10%). For instance, by summing recent heat stress damage and near future heat extreme increment, we predict up to 11%–24% heat-induced yield loss in Chongqing, Hunan, Anhui, and Zhejiang, the largest and most challenging changes that we find. Compared to temperature extremes, changes in growing season precipitation and its effects on tea yield are marginal (figure 5(E)). Under 2.0 °C warming scenarios, cold and heat extremes are expected to change in a similar pattern as 1.5 °C (figure 5). Yields are likely to benefit more from less cold stress, but there is also a notably higher risk of extreme heat damage (figure 5(D)). In extreme cases up around 14%–26% of heat-induced yield loss at the Yangtze River regions is anticipated. The uncertainty (± one standard deviation) of individual projections in figure 5 is available in supplementary figure 9.

4. Discussion

Climate change, especially temperature increase and consequent heat stress, is detrimental to several major crops according to statistical and process-based model approaches [1–4, 40]. High temperature-induced tea yield decline has also been reported in India [21] and Sri Lanka [22] and this loss is related to the monthly mean temperature. However, few studies have investigated cold or heat extremes-induced tea yield reductions. By applying a panel regression approach, our study, for the first time, quantified the relationships between temperature extremes and tea yield reduction.
production in China, demonstrating vulnerability to both cold and heat stress during 1990–2016. The substantial cold stress damage found in China suggests that tea production is more affected by cold than heat extremes at present climate. A study that used data from 1972 to 2014 showed that the tea crop in the Fujian province, eastern China, was at a higher risk from cold stress than heat stress [41], which is consistent with the findings of this study. Projections using 21 GCMs suggested that strong shifts from cold to heat stress will cover all tea production zones (supplementary figures 7 and 8). The notable increase in tea yields above 28° N indicates that northern regions (>28° N) in China will become more suitable for tea production due to the substantial cold alleviation. Climate warming seems to expand suitable tea cultivation areas towards cooler regions. Besides, the unexpected overall positive impacts of climate change on tea production (supplementary figures 7 and 8), indicates that climate warming is redistributing growing season temperature to more favorable ranges for tea production across study areas. A recent process-model based study reported similar positive outcomes of climate change on tea yields over China [42]. However, we also expect more heat-induced yields losses in southern regions, such as in Guangdong and Guangxi provinces and parts of the Yangtze River regions, if no effective adaptation strategies are applied (figure 5). Nevertheless, considerable uncertainty for estimating heat stress impacts remains (figure 2). This is partly due to only a handful of samples were affected by heat stress during the

Figure 5. Future cold stress-(A), (B), heat stress-(C), (D) and precipitation-(E), (F) induced yield changes comparing to the present climate when the 1.5 °C and 2.0 °C warming scenarios were used.
study period (supplementary figure 4), since sufficient sample size is crucial to accurately estimate the coefficient [43]. We highly encourage future studies could conduct field experiments to further narrow down the confidence interval and reduce the uncertainties for quantifying heat stress impacts, especially for the case when daily mean temperate exceeds the historical records. Besides, seasonal drought events, common in the subtropical humid regions of China, from July to September [44, 45] would limit nutrient uptake, even when there is an adequate supply of soil nutrients [46], which may also occur concurrently with the heat extremes and pose additive negative effects on tea production. Although climate warming would potentially increase tea yields over China, addressing the regional difference of extreme temperature shifts is still necessary and urgent for adapting tea production to climate change.

Our projections suggest tea cultivation in parts of the Yangtze River regions and southern China (<25° N) would benefit from investments in adaptation. Tea plantations are often located in mountainous regions where irrigation is infeasible, but other practices could benefit tea production in the new climate. These include planting shade trees or using mulching to cope with the more frequent heat extreme events in the near future [17, 47]. Diversifying farming systems might also increase the resilience of farmers to fluctuating climate conditions. In this study, we have emphasized the historical impacts of heat and cold extremes on tea productivity and the effects of future warming climate scenarios. Future research should consider how higher temperatures and frequent weather extremes (drought, heatwave, etc) may increase the risk of pest damage and diseases [48]. To the extent that pest damages increase, the actual yield loss triggered by temperature extremes in this study may be underestimated. As a perennial crop, tea yield could also be affected by the prior season's climate conditions and the months outside of our study's defined growing season. Future studies could adopt specified local growing period if sufficient data are available. Statistical model, in general, lacks systematic biological mechanisms. Utilizing a statistical approach might lead to a limited ability to fully explain the complex interaction between the tea crop and environmental conditions. We hope this study will provide useful information (e.g. temperature thresholds for cold and heat stress) to further improve the performance of contemporary process-based crop models to project climate responses, particularly for temperature extremes. To overcome the drawbacks of the non-mechanistic model, future studies could consider a hybrid physical and data-driven statistical model to better represent extreme climate events. Although temperature and precipitation are usually considered as the primary climate factors to affect crop yield [3, 32–34], other factors such as soil moisture and rising atmospheric CO₂ might also affect tea yields but are not explicitly accounted for in this study due to the limitation of the statistical approach or data scarcity issue. Nevertheless, we only considered the total amount of growing season precipitation but overlooked its time distribution. More studies and experiments will be beneficial to understand the adaptability of tea production to the incoming intensified heat extremes, including expanding beyond modeling tea yield to consider the quality of the harvested product [11, 25].

We quantified the vulnerability of tea yields to temperature extremes across the tea growing regions of China (figure 2). We found that historical cold stress caused greater yield reductions across China compared to heat stress. Southern China (<~25° N) will be more susceptible to heat extremes, even if only the lower 1.5 °C temperature goal outlined in the Paris Agreement is reached. Given the importance of tea to rural economies and human well-being, we urge further studies that examine the climate change on tea productivity and quality across globe.

Data availability statement

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

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