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Influence of multi-timescale precipitation indices on primary tea production in Baoshan, Yunnan, China

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Abstract

The regional economy in Yunnan, Southwest China, relies heavily on tea production. Both the quality and amount of tea production are sensitive to extreme climate events, but exactly how different timescale climate events influence tea production remains unknown. In this study, we explore the dynamic responses of tea production indices in Baoshan, Yunnan to 6 multi-timescale precipitation indices (MPIs) at lags of up to 20 years. The results are as follows: (1) Wet injury caused by precipitation during summer and autumn is a prominent threat to annual tea production in Baoshan, which leads to negative impacts on annual tea yield and raw tea price, with the impact on the latter mainly reflected in tea quality during the primary processing for black tea and green tea. (2) Annual tea yield and raw tea price are negatively correlated with CDD (consecutive dry days) and R20 (very heavy precipitation days) at lags greater than one year. (3) Spring tea yield and raw tea price are negatively correlated with spring precipitation, but positively correlated with days in the winter-spring dormancy period of tea plant (WSDP) and precipitation in WSDP; the positive correlation of days in WSDP is the most prominent with spring tea production of the 3 MPIs. (4) Unlike other famous tea areas, lower R20 frequency in Baoshan is not associated with high rates of soil erosion, but the lack of drainage ditches in the tea garden still means that continuous precipitation or heavy rainfall are a risk to Baoshan tea production. The insights provided by this study will help farmers and other decision-makers to understand the mechanism of MPIs’ influence on tea production, inform regional responses in tea plantation management to the observed different precipitation trends, and improve future management decisions under a changing climate.

1. Introduction

Tea is one of the most widely consumed beverages in the world, second only to water [1–3], and contributes to dietary patterns that could potentially be more sustainable and healthier [4]. As the first country in the world to drink and grow tea, China is now the world’s largest tea-producing country, with an output of 2.8 million tons annually, accounting for more than 43% of total global tea production and 60% of the global tea plantation area [5, 6]. With the largest area, second largest production, and third largest output value in China [7], the Yunnan tea industry has become an important economic pillar of more than 77% of counties (cities) in Yunnan...
Province. The tea industry provides the main income source for millions of mountain farmers, is an important
tax revenue source for local governments, and also plays a pivotal role in the sustainable development of rural
areas [8]. Since tea plant cultivation and collection are very sensitive to extreme climate events [6],
understanding the influence of extreme climate events on tea production is, therefore, crucial in planning
adaptation activities and regional development.

Over recent years there has been considerable progress towards quantifying and understanding the effects of
meteorological variations on tea production in different regions of the world. This includes exploring the
response of tea quality to variations in both precipitation and temperature, which are the most two important
climate factors that affect tea production. Many studies have elaborated on the relationship between tea quality
and temperature variations: high and low-temperature treatments both lead to change in ascorbic acid (AsA)
content in tea leaves [2]. The synthesis of soluble substances decreased in concert with protective effects when
the low temperature or duration of stress exceeded the maximum tolerance of tea plant in Guizhou, China [9].
Sub high temperature (SHT) of 35 °C gradually decrease theanine concentration in tea leaves due to the SHT-
induced suppression in theanine biosynthetic genes [3]. More research has focused on the correlation between
temperature and tea yield variations. In Kenya, frequent frost occurrences had devastating effects on agricultural
productivity [10], while tea yields in 2040–2070 are projected to decrease by 10% relative to 1990–2020 due to
to rising temperature [11]. In Assam, India, increasing monthly average temperature (above 26.6 °C) and
precipitation intensity have generally negative effects on tea yield [12]. Similarly, the hotter and wetter climate
will have a detrimental effect on Sri Lankan tea production, and a decline of 12% in annual tea production is
predicted by mid-century [13]. In China, dominating cold extremes influence more than half of tea production
in the present climate, with a maximum of 36.3% reduced annual yield [8]. In the future at both the 1.5 °C and
2.0 °C global warming levels, intensified heat extremes will lead to losses (up to 14%–26% tea yield) estimated at
the Yangtze River (~30° N) and southern China (<~25° N) regions [6].

In addition, meteorological factors can also impact the pricing of raw tea to some extent [7]. When production
factors (i.e., the cost of labor and tea garden management, etc) are relatively stable, the change in meteorological
factors is the main factor determining the growth and germination of tea plants, which will directly affect the
classification of tea quality and even the price of raw tea. For example, spring frost can damage tea buds and
decrease their economic value [14–16], and the resulting economic losses are related to the extent and severity of
frost that occurs during the tea bud and leaf plucking period. Springtime temperature changes will directly affect
the speed of shoot growth and the determination of tea picking time [14], resulting in large differences in raw tea
prices [7], sometimes exceeding 1000 Chinese yuan/kg [17].

As mentioned above, the response of primary tea production to temperature has received considerable
attention [2, 3, 6, 9–13, 14–17], resulting in abundant and influential conclusions. By comparison, the impact of
precipitation on tea production is less well understood, with very few studies exploring the impact of multi-
timescale precipitation indices (including extreme precipitation) on tea production, or investigating the effect of
precipitation on primary processing of different types of tea [9,10]. In addition, the short duration of tea production
records used in previous research [12, 24–28] limits the reliability of such conclusions.

Previous studies have found that changing rainfall patterns can affect tea plant growth, flavour, and potential
health benefits [25, 29–32], hence this warrants further attention and study. In Yunnan Province, China,
precipitation variations during different monsoon periods have been shown to have different influences on the
macro- and micronutrient concentrations of tea plants [33]. Other researchers have explored links between tea
yield and precipitation variations, highlighting considerable regional differences, and suggesting complex
underlying relationships and the importance of local conditions. For example, reduced tea yield is associated
with increased precipitation intensity in Assam, India [12], while increased monthly rainfall had a significant
positive effect on monthly tea yield in the same region [27]. In Sri Lanka, it is predicted that tea yield would
increase with increasing rainfall across all elevations [34], while other researchers insist that tea production may
be negatively affected by predicted long-term increases in rainfall in Sri Lanka [13]. In China, daytime rainfall in
spring can decrease economic outputs of tea in Zhejiang tea area [17]. In Xishuangbanna, Yunnan, China, tea
yield is up to 50% higher during the summer monsoon than during the spring drought [24].

7 Although there are many complex influencing factors that can affect the pricing of raw tea, such as quality, variety, producing area,
meteorological factors change, cost of production factors, supply and demand, changes in consumer preferences, policies, market
mechanism, etc [14, 17–23], it is undeniable that pricing according to tea quality is still the basic requirement of the market price mechanism,
and raw tea price is always significantly associated with the biochemical parameters and various quality attributes [21, 14].
8 The spring tea price depends on the time of tea production and the grade of tea buds, and earlier plucking time usually results in higher
price. For example, the price of tea produced by superfine tea buds and leaves of the special early-onset cultivars is more than 1000 yuan per
kilo higher than that produced by superfine tea buds and leaves of the late-onset cultivars [17].
9 The primary processing of black tea includes withering, rolling, fermentation, and drying.
10 The primary processing of green tea includes de-enzyme, rolling, and drying.
More generally, the increasing intensity and frequency of precipitation extremes in Yunnan \([35–39]\) has changed the local growing conditions, contributing to significant instability in the tea industry, and increased the vulnerability of tea production in high-risk regions for climate change in Yunnan \([29, 33]\). Consequently, there is an urgent need to quantify the influences of precipitation variability, with a focus on multi-timescale precipitation that affect tea production in Yunnan.

The objective of this study is to reveal the dynamic influence of Multi-timescale Precipitation Indices (MPIs), including Extreme Precipitation Indices (EPIs), on primary tea production indices (i.e. annual/spring tea yield and raw tea price) based on 24-year records in Baoshan, Yunnan. To our knowledge, this is the first study devoted to exploring the relationship between raw tea price, different steps of the tea primary processing, and multi-decadal precipitation records.

The remainder of the manuscript is organized as follows. In section 2, we introduce the data and study area. Section 3 introduces the analysis methods. The results are presented in section 4. Section 5 summarizes the major findings, discusses the corresponding countermeasures for specific MPI influences on tea production in Baoshan, and considers the potential influences of this research on society.

2. Study sites and data description

Baoshan is regarded as a unique area in terms of landscape and biodiversity. The region includes Longyang District, Tengchong County, Shidian County, Longling County and Changning County in west Yunnan \((24°46′–25°38′N, 98°43′–99°26′E, \text{as shown in figure 1})\) and is located in the southern part of the Hengduan Mountains, with mountainous and semi-mountainous areas accounting for 92.6% of its total territory. With large mountains (Gaoligong and Nu Mountains) and international rivers (Up-Mekong, Nu and Irrawaddy Rivers) shaping the landscape, Baoshan is characterized by a climate that changes with altitude, experiencing a monsoon climate in the low-latitude plateau and six climate types \([40, 41]\) between 335m and 3780 m above mean sea-level (see in supplementary materials (available online at stacks.iop.org/ERC/4/025009/mmedia)). The history of Baoshan tea-producing areas (BTP) goes back more than 3000 years. Due to its advantages in terms of climate, environmental resources (e.g. soil, biodiversity, traditional planting methods) and convenient access to transportation, Baoshan is one of the most suitable areas for Yunnan big-leaf tea species (the best raw material for black tea and Pu’er tea) and small-leaf tea species at high elevations. Compared with other overexploited tea areas, there are still many undeveloped areas for wild tea cultivation in Baoshan \([42, 43]\) that have great potential for exploration and research value. The BTP is, therefore, a region of considerable interest and selected to quantitatively evaluate the responses of tea production indices (yield and raw tea price) to MPIs.
The following daily data are used in our analysis:

1. Observed daily precipitation data at five meteorological sites [11] (Longyang, Changning, Tengchong, Shidian, and Longling; see figure 1) during the period of 1960–2019, provided by China Meteorological Data Network (http://data.cma.cn/).

2. Annual tea yield and raw tea price, annual yield and raw tea price of spring tea, and tea plantation area (TPA) in Baoshan during the period of 1996–2019, compiled by Statistical Bureau of Yunnan Province, in the statistical yearbook.

In this study, we focus on the primary tea yield rather than various processed tea products. Raw tea is made from fresh tea leaves after primary processing. Compared with purified tea prices, raw tea prices are more directly influenced by tea quality and, therefore, climate. We note that, before 1995, the variations in raw tea prices in Baoshan were mainly determined by the government under the influence of the planned economy and did not reflect the real influences of tea quality and market control.

Table 1 gives the definitions of 6 MPIs used in our analysis. Among the 6 MPIs, 2 indices of Extreme Precipitation Indices (EPIs) are here quantified by precipitation indices selected from the Expert Team on Climate Change Detection and Indices (ETCCDI) list. These were calculated from the daily precipitation observations for the five meteorological sites in Baoshan using the R climdex software.

### 3. Analysis method

The Vector Autoregressive (VAR) model proposed by Sims [44] is an extension of the univariate autoregressive model to multivariate time series data. Compared with conventional simultaneous equations models, the VAR model has several advantages. Firstly, it is built on the mathematical and statistical properties of data rather than assumptions based on theory. Secondly, the VAR model takes the form of multiple simultaneous equations; the endogenous variables in each equation form a regression with the lagged values of itself and the other exogenous variables, to capture the complex dynamic relationships between the variables [45–47]. Thirdly, the approach allows us to consider both long-run and short-run impacts justified by economic and climate considerations. In this study, we use Vector Autoregressive (VAR) models to explore how tea production is influenced by MPIs on different timescales during 1996–2019. The mathematical expressions of the general VAR(p) model are as follows:

#### Table 1. Definitions of the 6 Multi-timescale Precipitation Indices (MPIs) used in this study.

| Type | Index Name | Definitions | Unit |
|------|------------|-------------|------|
| Abundant and continuous precipitation | Precipitation during summer and autumn (Pre-SA) | Sum of precipitation from June to October per calendar year | mm |
| Extreme precipitation indices (EPI) | Number of very heavy precipitation days (R20) | Annual count of days when PRCP ≥ 20 mm per calendar year | Days |
| | Consecutive dry days (CDD) | Maximum number of consecutive days with RR < 1 mm per calendar year | Days |
| Precipitation indices during the winter-spring dormancy period of tea plant (WSDP for short) | Number of days in winter-spring dormancy period of tea plant (D-WSDP) | Maximum number of consecutive days with mean temperature < 10°C per calendar year | Days |
| | Precipitation in WSDP (Pre-WSDP) | Sum of precipitation during WSDP per calendar year | mm |
| Spring precipitation | Spring precipitation (Pre-spring) | Sum of precipitation from March to May per calendar year | mm |

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11 The five meteorological observation stations used in the study belong to national reference climatological station or national base station, which are located in the five tea areas of Baoshan, and can better reflect the characteristics of local meteorological elements in a large range of the area. The recorded meteorological data of the five stations have been subject to quality control, which are representative, accurate and comparable. In particular, Tengchong Observatory is listed as one of the stations of the Global Climate Observing System (GCOS) by the World Meteorological Organization (WMO). Its meteorological data participates in international exchanges and is certified as a high-quality observation for the GCOS surface network.

12 A variable is said to be endogenous within the model, if its value is determined or influenced by one or more of the independent variables (excluding itself). In contrast to endogenous variables, exogenous variables are considered independent. It is a factor whose value is determined by factors or variables outside the causal system under study.
\[
Y_t = C + \Phi_1 Y_{t-1} + \Phi_2 Y_{t-2} + \cdots + \Phi_p Y_{t-p} + HX_t + \varepsilon_t \\
t = 1, \ldots, T
\]  
(1)

where \( p \) is the order of the lag in the VAR model, \( t \) is the unit of time, \( Y_t = (y_{1t}, y_{2t}, \ldots, y_{kt})' \) is the \( k \times 1 \) vector of endogenous variables and \( k \) is the number of endogenous variables, \( X_t = (x_{1t}, x_{2t}, \ldots, x_{mt})' \) is a \( q \times 1 \) vector of exogenous variables with \( q \) being the number of exogenous variables, \( y_{jt} \) and \( x_{jt} \) are respectively the \( i \)-th (\( i = 1, \ldots, k \)) endogenous variable and the \( j \)-th (\( j = 1, \ldots, q \)) exogenous variable at time \( t \). \( \Phi_1, \Phi_2, \ldots, \Phi_p \) and \( H \) are \( k \times k \) and \( k \times q \) coefficients matrices to be estimated, the error term \( \varepsilon_t \) is the \( k \times 1 \) vector of Gaussian white noise process \( \varepsilon_t \), and \( C \) is a \( k \times 1 \) vector of intercept term.

The VAR model (1) describes that the endogenous variables \( Y_t \) are affected by the value of the lagged endogenous variables (up to lag \( p \)) and the contemporaneous value of the exogenous variable at time \( t \). According to the structural form of VAR model, \( Y_{t-1} \) is affected by \( X_{t-1} \), and \( Y_{t-2} \) is also affected by \( X_{t-2} \) and so on, which means that the exogenous variables \( X_t \) is affected by the values of change in variable \( X_t \) not only at time \( t \) but also at time \( t-1, t-2, t-3 \) and so on. This relationship is consistent with the production features of perennial crops such as tea trees.

If the VAR model satisfies the stationary condition, we can obtain the most useful form of the model in which \( Y_t \) can be written as an infinite linear combination of the past values of the exogenous variables, i.e.

\[
Y_t = B + A_0 X_t + A_1 X_{t-1} + A_2 X_{t-2} + \cdots + u_t
\]  
(2)

where \( B \) is the \( k \times 1 \) vector of constants, \( u_t \) is an infinite moving average of the random errors \( \varepsilon_t \), and \( A_m (m = 0, 1, 2, \ldots, \infty) \) are \( k \times q \) matrices which can reflect the influence from the lag \( m (m = 0, 1, 2, \ldots, \infty) \) of exogenous variables. The definitions of \( B, u_t \) and \( A_m (m = 0, 1, 2, \ldots, \infty) \) are given in supplementary materials 9. Specifically, the \( i \)-th (\( i = 1, \ldots, k \)) endogenous variable at time \( t \) can be expanded as

\[
y_{it} = b_i + \sum_{j=1}^{q} (a_{ij}^{(0)} x_{jt} + a_{ij}^{(1)} x_{j(t-1)} + a_{ij}^{(2)} x_{j(t-2)} + \cdots) + u_{it}
\]  
(3)

where \( b_i \) and \( u_{it} \) are respectively the \( i \)-th element of \( B \) and \( u_t \), and \( a_{ij}^{(m)} \) is the \( ij \)-th element of coefficient matrix \( A_m (m = 0, 1, 2, \ldots, \infty) \).

When the VAR model is written in the form of equation (3), the coefficients can be expressed as

\[
a_{ij}^{(m)} = \frac{\partial y_{it}}{\partial x_{jt-m}}, \quad i = 1, 2, \ldots, k; \quad j = 1, 2, \ldots, q; \quad m = 0, 1, 2, \ldots, \infty,
\]

which are equivalent to a time-dependent gradient in ordinary regression analysis. The coefficients \( a_{ij}^{(m)} \) describe how a change in the \( j \)-th exogenous variable at time \( t-m \) (i.e. \( x_{jt-m} \)) influences the \( i \)-th endogenous variable at time \( t \) (i.e. \( y_{it} \)). The index \( m \) represents a lag in the exogenous variable, which allows the model to quantify the historical influence of the exogenous variable on the endogenous variable.

Based on the above analysis, the VAR model is suitable for describing the correlation analysis between tea production and climate variation. In this study, we build 4 different VAR models to analyze the influence of MPI indices (exogenous variables) on tea production indices (endogenous variables) during the period of 1996–2019. Since tea plantation area has close relationship with both yield and raw tea price through the lag in the endogenous variable, we chose plantation area as one of the endogenous variables. However, we do not plot how tea plantation area responds to precipitation in this paper, since tea plantation area is not only related to tea yield and raw tea price, but is also significantly affected by other factors (including market function, the initiative of tea farmers to manage tea gardens, and government planning). Because it is difficult to quantify these additional correlation factors within the VAR model, this paper focuses on the correlation between MPI indices and tea yield/raw tea price, and not tea plantation area. The standard statistical procedures of required to build a robust VAR model are given in supplementary materials.

4. Results

We first focus on the dynamic effects of MPIs on tea yield and raw tea price across different timescales. To make the data more normally-distributed and improve the VAR model fits, all variables were transformed by taking their natural logarithms\(^{13}\). Table 2 gives the descriptive statistics of the transformed data—the names start with the expression ‘LN’ to show how they have been transformed.

\(^{13}\) The Gaussian white noise process is a random process with zero mean and unknown positive definite covariance matrix.

\(^{14}\) The logarithm transformation is an important mathematical tool of data transformation. Since the logarithm function is monotonically increasing function, the relative relation of the data will not be changed after taking the logarithm. There are two purposes for the logarithm transformation: \( \circ \) the logarithm function tends to squeeze the larger values and stretches out the smaller values in the data, which can decrease the variability of data, make data more stable and less skewed, thus can make the data more normal distributed. \( \circ \) The regression coefficient on the logarithm scale coincides with the definition of elasticity, which refers to the property of a certain percentage of changes in one variable relative to another\(^{48}\).
We employ three VAR models, outlined by equations (S3), (S5) and (S6) in supplementary materials. The vector of endogenous variables, $Y_t$, is the same for each of the 3 VAR models, and consists of the following:

- annual tea yield in year $t$ ($\text{LNYIELD}_t; i = 1$)
- annual raw tea price in year $t$ ($\text{LNPRICE}_t; i = 2$)
- annual tea plantation area in year $t$ ($\text{LNTPA}_t; i = 3$).

The $i = 1, 2, 3$ indices correspond to the notation in equation (3). Each VAR model also includes a single exogenous variable, with Pre-SA, CDD and R20 being the exogenous variable in equation (S3), (S5) and (S6) in supplementary materials, respectively.

Equation (S9) in the supplementary materials is formulated slightly differently than (S3), (S5) and (S6), which helps reveal the influence of other precipitation indices on spring tea production. In equation (S9), the vector of endogenous variables $Y_t$ consists of the following:

- annual spring tea yield in year $t$ ($\text{LNS-YIELD}_t; i = 1$)
- annual spring raw tea price in year $t$ ($\text{LNS-PRICE}_t; i = 2$)
- annual tea plantation area in year $t$ ($\text{LNTPA}_t; i = 3$).

The vector of exogenous variables $X_t$ consists of:

- precipitation in WSDP in year $t$ ($\text{LNPre-WSDP}_t; j = 1$)
- spring precipitation in year $t$ ($\text{LNPre-SPRING}_t; j = 2$)
- number of days in WSDP in year $t$ ($\text{LND-WSDP}_t; j = 3$).

Using the EVIEWS10 software, we calculate the matrix $A_m$ ($m = 0, 1, \cdots, \infty$) for these 4 VAR models by applying the methodology explained in supplementary materials. Then, as described in equation (3), we plot the elements $a^{(m)}_{ij}$ as a function of the lag $m$ for $i = 1, 2, \cdots, k; j = 1, 2, \cdots, q; m = 0, 1, 2, \cdots, \infty$ to reveal the dynamic response characteristics of each VAR model and trace out the time-dependent influence of the MPIs on tea yield and raw tea price. More specifically, figures 2–5 show how a change in $j$-th exogenous variable at time $t$ influences the $i$-th endogenous variable at time $t$, for different values of the lag $m$. Although the maximum allowed value of $m$ is infinite, it is not physically meaningful to plot $a^{(m)}_{ij}$ for values of $m$ beyond the duration of the available data. Since we observe that $a^{(m)}_{ij}$ asymptotically tends to zero as $m$ increases, we truncate the figures 2–5 at a maximum lag of $m = 20$ years when the coefficients go slowly to zeros.

The specific modeling includes the following steps. In the first step, the stationarity of time series is determined. The Augmented Dickey-Fuller (ADF) unit root test is widely used to determine whether the time series data are stationary. In the second step, the Johansen co-integration test was conducted to verify the existence of co-integration among several variables. If the variables are co-integrated, there may also be a set of co-integration restrictions that would improve the efficiency of the estimation. In the third step, we perform the Akaike Information Criterion, Schwarz Criterion tests and Hannan-Quinn information criterion to determine the optimal lag length of the VAR models. Additionally, it is necessary to perform the stability test of the VAR model. Only when the VAR model is stable, the estimated results can be used effectively. The results of the diagnostic
checking of the estimated VAR models include the AR root graph autocorrelation and heteroscedasticity test. In this study, four VAR models is built, and more details and specific results of them can be seen in supplementary materials.

4.1. Dynamic influences of summer and autumn precipitation on annual tea production indices based on the 1st VAR model

Since Pre-SA accounts for almost 70% of total annual precipitation in Baoshan, it makes sense to study the relationship between Pre-SA and annual tea production. We establish the 1st VAR model in equation (S3) in supplementary materials. More details for construction of the 1st VAR model are given in supplementary materials.

The characteristics of Pre-SA during 1996–2019 in Baoshan (see table 3) show that precipitation during summer and autumn is generally continuous and abundant, which can result in wet injuries\(^\text{15}\) in tea gardens. Solving equation (S4) in supplementary materials reveals the impact of abundant and continuous precipitation on annual tea production, which is shown in figure 2. These coefficients show the magnitude and sign of the relationship between the endogenous variables and exogenous variables at previous times. A non-zero value of

\(\text{Figure 2. Change in annual tea yield and raw tea price per change in the precipitation during summer and autumn (Pre-SA; } j = 1), \text{ shown as a function of lag (years). Left-hand panel shows the time-dependent relationship for yield (i = 1); right-hand panel shows the time-dependent relationship for raw tea price (i = 2).}\)

\(\text{Figure 3. Change in annual tea yield and raw tea price per change in annual maximum number of consecutive dry days (CDD; } j = 1), \text{ shown as a function of lag (years). Left-hand panel shows the time-dependent relationship for yield (i = 1); right-hand panel shows the time-dependent relationship for price (i = 2).}\)

\(^{15}\) The process of wet injuries caused by Pre-SA in Baoshan is described in supplementary materials.
For $m = 0$ indicates a contemporaneous relationship between the $j$-th exogenous and $i$-th endogenous variables. Similarly, non-zero values of $a_{ij}$ for $m > 0$ indicate lagged effects, i.e. the exogenous variable influences the endogenous variable at later times.

More specifically, the left-hand panel of figure 2 shows the time-dependent response of tea yield to Pre-SA, while the right-hand panel shows the time-dependent response of raw tea price to Pre-SA. These plots show that both annual tea yield and raw tea price decrease with increasing Pre-SA, meaning that the time-dependent gradients are negative. For example, an increase in current Pre-SA by 1% is associated with a negative change of 0.126% in current annual tea yield. There can be a lagged effect, with the correlation of current Pre-SA with annual raw tea price reaching its maximum value (-0.539%) in the next year (i.e. $m = 1$) and decreasing after that (i.e. $m > 1$). Plausible physical explanations for these relationships are described below.

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**Figure 4.** Change in annual tea yield and raw tea price per change in annual count of days with rainfall $>20$mm ($R_{20}; j = 1$), shown as a function of lag (years). Left-hand panel shows the time-dependent relationship for yield ($i = 1$); right-hand panel shows the time-dependent relationship for raw tea price ($i = 2$).

**Figure 5.** Change in spring tea yield and raw tea price per change in days in winter-spring dormancy period of tea plant (D-WSDP) (left-hand column; $j = 1$), precipitation in WSDP (Pre-WSDP) (middle column; $j = 2$), and spring precipitation (Pre-spring; $j = 3$) (right-hand column), shown as a function of lag (years). The top row shows the time-dependent relationship for yield ($i = 1$); the bottom row shows the time-dependent relationship for raw tea price ($i = 2$).
Table 3. Characteristics of Pre-SA during 1996–2019.

|                      | Longyang | Tengchong | Longling | Shidian | Changing |
|----------------------|----------|-----------|----------|---------|----------|
| Average summer and autumn precipitation (mm) | 721.2    | 1094.1    | 1573.2   | 682.1   | 893.5    |
| Percentage 2 in the M-SA years (%) | 91.7%    | 97.7%     | 99.4%    | 94.1%   | 93%      |
| Percentage 2 in the L-SA years (%) | 83.1%    | 95.9%     | 97.3%    | 87%     | 87.5%    |
| Percentage 2 in the years with normal summer and autumn precipitation (%) | 78.6%    | 97%       | 97.7%    | 87.2%   | 91.7%    |

Notes:
1. Percentage 2: Percentage of continuous precipitation in summer and autumn precipitation.
2. M-SA years: the years with more summer and autumn precipitation (≥10%) than average during the baseline period (1981–2010).
3. L-SA years: the years with less summer and autumn precipitation (≤10%) than average during the baseline period (1981–2010).

Table 4. Percentage of years with CDD ≥ 20 in the tea growing period for 5 sites within Baoshan.

|       | Longyang | Tengchong | Longling | Shidian | Changing |
|-------|----------|-----------|----------|---------|----------|
| Percentage | 39.10%   | 43.30%    | 34.80%   | 34.80%  | 34.80%   |

An increase in Pre-SA means that soil moisture is likely to increase, also reducing the air–water ratio in the soil. As a result, tea plant growth is negatively impacted because of insufficient oxygen and restricted root respiration, which then leads to decreased tea yield [25, 29]. In addition, continuous rainfall will further increase difficulties in picking [14] and later processing, which not only result in reduced tea yield, but also in tea quality and raw tea price. Our results are consistent with previous research which showed that increased precipitation leads to a significant decrease in tea functional quality, as determined by concentrations of individual catechin secondary metabolites and total methylxanthine concentrations [12, 24]. The collected shoots or leaves usually contain dew/rainwater on their surface [49], suggesting that increased Pre-SA could lead to excessive water content in the harvested shoots, which is bad for the primary processing of tea 16, and has negative impact on raw tea price according to the Value and Classification of Tea Quality (VCTQ for short) in China (see supplementary materials).

4.2. Dynamic influences of extreme precipitation indices (EPI: CDD and R20) on annual tea production indices based on VAR models

We establish the 2nd and 3rd VAR models in equations (S5) and (S6) in supplementary materials to evaluate the response of annual tea production indices to CDD and R20 variations. As for equation (S5), we set a maximum lag of $p = 2$ for the endogenous variables. As such, equation (S5) describes the linear dependence of yield, raw tea price and plantation area at time $t$, on their previous values at time $t - 1$ and $t - 2$, and on the annual number of consecutive dry days at time $t$. Similarly, equation (S6) describes the linear dependence of yield, raw tea price and plantation area at time $t$, on their previous values at time $t - 1$ and $t - 2$, and on the annual number of very heavy precipitation days at time $t$. The temporal response of annual tea yield and raw tea price to CDD and R20 is shown in figures 3 and 4, and described below.

4.2.1. Response of annual tea production indices variation to CDD variation

Figure 3 shows that an increase in CDD in Baoshan is associated with a decrease in both annual tea yield and raw tea price. For example, an increase in current CDD by 1% leads to a negative change in current annual tea yield by 0.047%, and raw tea price by 0.082%. The negative correlation of CDD with annual tea yield generally decreases with time (i.e., larger $m$), while the correlation of CDD with raw tea price reaches its maximum value ($-0.096\%$) at a lag of one year ($m = 1$) and decreases after that.

This result is broadly expected because moisture availability is a key element for tea plant growth, being not only the material for photosynthesis to produce organic matter, but also the medium for transporting nutrients within the plant: fertilizers and mineral nutrients in the soil can only be absorbed and utilized by the tea roots under suitable moisture conditions. As such, the occurrence of CDD will reduce the soil moisture content, which negatively impacts the synthesis and transportation of effective ingredients within the tea plant. This can delay the germination of tea plant and affect tea quality, leading to a decline in both annual tea yield and raw tea price and plantation area at time $t$, on their previous values at time $t - 1$ and $t - 2$, and on the annual number of very heavy precipitation days at time $t$. The temporal response of annual tea yield and raw tea price to CDD and R20 is shown in figures 3 and 4, and described below.

Further information for the steps of tea primary processing is provided in supplementary materials.
price [17]. We note that from 1996 to 2019, about 40% of years experienced dry periods during the tea plant growing season (shown in table 4 [17]).

4.2.2. Response of annual tea production indices variation to R20 variation

Figure 4 shows that an increase in R20 is typically associated with reductions in both annual tea yield and raw tea price. The correlation of R20 with annual raw tea price reaches its maximum value (−0.349%) after one year ($m = 1$) and decreases after that ($m > 1$). Unlike some tea areas in Assam and China (Fujian province) [25, 50, 51], the lower frequency of occurrence of Baoshan R20 is not associated with high rates of soil erosion, especially under terraced tea plantation with reverse slope [18]. Due to this, local tea farmers in Baoshan have tended to neglect the importance of drainage ditch facilities in tea gardens. In addition, the high cost of excavation and management for drainage ditches means that drainage ditch facilities are currently found in only 10%–15% of tea plantations in Baoshan. As such, higher values of R20 will tend to increase surface runoff and nutrient loss [51] in tea gardens without sufficient drainage facilities. This has a negative influence on the growth of tea trees and budding in the following year, which potentially explains why an increase in R20 is associated with bad effect on tea yield and raw tea price in the following year and beyond, i.e. $m \geq 1$.

4.3. Dynamic influences of other precipitation indices on spring tea production indices based on the spring tea production VAR model

Fresh tea leaves in Baoshan can be picked throughout the year in spring, summer and autumn, with spring tea accounting for 46% of annual yield each year. In addition, after storing nutrients for the whole winter/WSDP, spring raw tea price is the highest than in other seasons, due to the best VCTQ during the year [24].

Because of this, we want to further inspect the dynamic influence of other precipitation indices on spring tea production, using the VAR approach. According to the criteria described in supplementary materials, the optimal lag length is 2. As such, equation (S9) in supplementary materials describes the linear dependence of spring tea yield, spring raw tea price and plantation area at time $t$, on their previous values at time $t−1$ and $t−2$, and on precipitation in WSDP, spring precipitation and number of days in WSDP at time $t$.

To solve equation (S10) we first need to calculate the precipitation and number of days during the WSDP in Baoshan. Previous studies [6, 31, 52] have shown that the tea tree WSDP occurs while temperatures are below approximately 10 °C. We can use this threshold to define the beginning and ending dates of the WSDP in Baoshan, as shown in supplementary materials.

4.3.1. Response of spring tea production to the variations of D-WSDP

An increase in D-WSDP (i.e. a long winter-spring dormancy period) is associated with increases in both spring yield and raw tea price (figures 5(a) and 5(d)). Compared with some famous tea areas in China, tea plants in Baoshan have a generally better living state due to the developed root system and helpful temperature variations during the WSDP, without higher frost risk [19]. Therefore, a longer WSDP allows the tea plant in Baoshan to absorb and store a greater quantity of beneficial nutrients. It also means that Baoshan tea area has advantageous climate conditions with excellent tea quality which is sometimes even better than other famous tea areas in Yunnan, according to tea farmers’ sensory evaluation.

4.3.2. Response of spring tea production to the variations of Pre-WSDP

As mentioned above, even during the WSDP, tea plants need water to maintain vital physiological activities [20]. Therefore, intermittent, moderate precipitation during the WSDP can ensure normal root activities, better tea plant growth and accumulation of effective nutrients for sprouting new buds in the spring. This means that an increase in current Pre-WSDP generally has a positive effect on both spring tea yield and tea quality, and is associated with increases in raw tea price of spring tea (figures 5(b) and 5(e)).

4.3.3. Response of spring tea production to the variations of Pre-spring

An increase in spring precipitation (i.e. Pre-spring) is followed by reduced yield and raw price for spring tea in Baoshan (figures 5(c) and 5(f)). Increased Pre-spring tends to coincide with lower temperatures, which makes the tea plant grow slowly, delay tea bud germination and decrease spring tea yield [25]. Increased Pre-spring is

17 According to the growth feature of tea plants, if CDD in tea growing period is less than 10 days, it may not have a negative impact on the germination of tea plants. However, if CDD in the growing period is greater than 15 days, the negative effect will become more obvious.

18 More explanations for this are given in supplementary materials.

19 More information of advantageous climate conditions for tea plant growth in Baoshan can be seen in supplementary materials.

20 This means that low levels of soil moisture during the WSDP will cause the plant to extend its roots downwards in search of water, consuming nutrients in the process. As a result, the roots will not be able to effectively synthesize sufficient nutrients for tea plant growth.
also associated with dense clouds and lower amount of sunlight reaching the tea plant. This reduces photosynthesis and accumulation of organic matter, leading to lower tea quality and decreased raw tea prices.

Figure 5 also shows that, for the spring tea production VAR model, the strongest influence on both spring tea yield and raw tea price are positive associations with D-WSDP, followed by the negative correlation of Pre-spring and then the positive effect of Pre-WSDP.

5. Discussion and conclusion

In this study, we have explored the influence of Multi-timescale Precipitation Indices (MPIs) on tea production indices based on the study in Baoshan, Yunnan Province for the period 1996–2019. We used Vector Autoregressive (VAR) models to evaluate the time-dependent response of multi-timescale tea production indices in Baoshan to the 6 MPIs. This novel approach is necessary for understanding risks to tea plants because they grow over many years meaning that tea yield, quality, and raw tea price can be affected by growing conditions in the current year, and previous years. The major influences of MPIs on tea production are summarized below: (1) Wet injury caused by Pre-SA is a prominent threat to annual tea production in Baoshan. Increased Pre-SA is associated with decreased annual tea yield and raw tea price, with the correlation with the latter mainly reflected in tea quality during the primary processing for black tea and green tea. (2) An increase in CDD is associated with decreased annual tea yield and raw tea price. The negative correlation of CDD with annual tea yield decreases with the time, while the correlation of CDD with raw tea price reaches its maximum value after one year and decreases after that. (3) Without sufficient drainage facilities in the tea garden of Baoshan, an increase in R20 is associated with decreased annual tea yield and raw tea price. The correlation of R20 with annual raw tea price reaches its maximum value after one year and decreases afterwards. (4) Due to the suitable temperature conditions in Baoshan during the WSDP, and the well-developed tea plant root system, increases in D-WSDP and Pre-WSDP are associated with increased raw tea price and yield for spring tea. In contrast, increased Pre-spring is associated with decreased spring tea yield and raw tea price. The positive correlation of D-WSDP is found have the largest effect on both spring tea yield and raw tea price, followed by the negative correlation of Pre-spring and positive correlation of Pre-WSDP. To illustrate these effects, the severe spring drought in 2013 suffered by Baoshan tea area is a good example. In this year, due to the prominent decrease in Pre-WSDP and increase in CDD, low levels of soil moisture caused tea plant roots to consume too many nutrients to stretch downwards for deeper underground water. In addition, the shorter WSDP also led to decreased ability of tea plants to absorb/store enough beneficial nutrients, hence germination slowed down or even stopped. This not only resulted in significantly decreased spring tea yield and raw tea price, but also led to decreased resistance of tea plants to the following wet injury caused by increase in Pre-SA and R20 in this year. Similarly, severe spring drought happened again in Baoshan tea area in 2021: from November 2020 to the end of April 2021, except for a three-day period of rain in late January, there was almost no effective precipitation in most tea areas of Baoshan, which means the rainfall was generally light and unable to infiltrate the soil. As a result, the germination of tea plants and the tea picking period have been delayed by nearly 20 days compared to normal years. In addition, pest damage has become more serious, leading to a significant decrease in spring tea yield.

Taking into account the current management of tea gardens in Baoshan, alongside the results outlined above, certain countermeasures and recommendations can be adopted to reduce negative influences, as follows: to prevent wet injury caused by Pre-SA and R20, ditching and drainage should be set up according to the local waterlogging situation and terrain. At the same time, scarification by deep plowing, timely pruning, and reasonable topdressing should also be adopted according to the appropriate technical specifications. Additional measures can also be considered specific to reducing tea gall disease caused by wet injury. In addition, Baoshan’s tea production could shift focus on the development of high-quality tea products, benefiting from the advantageous climate conditions and characteristics of local tea varieties. For example, new organic tea gardens can be cultivated in sunny areas with fertile soil in mountainous areas (at the altitude of no more than 2500m). Although the germination of tea plants may be slightly delayed due to lower temperatures at higher altitude, the WSDP will be longer, and the tea quality throughout a year will be generally better than in lower altitude areas of Baoshan.

This study fills a key research gap in the region and helps to reveal the complex regional response of the tea economy to seasonal and natural climate variations. The enhanced understanding provided by this study can help farmers and other decision-makers to understand how MPIs can influence tea production, inform tea plantation management responses to precipitation indices, particularly through the targeted use of ditching and drainage in tea plantations, and by influencing the timing of different activities in the planting, growing and harvesting seasons in this specific region. The relationships derived from the approach used here could also be

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21 Scirtothrips dorsalis Hood.
22 More detailed information of wet injury to tea plants caused or Pre-SA and heavy rainfall indices in Baoshan and countermeasures are given in supplementary materials.
combined with skillful short- to medium-term climate forecasts (e.g. seasonal forecasts) to improve climate resilience in this key industry. Further, this understanding should allow a more informed approach to future tea plantation management under a changing climate, in this region and elsewhere in the world.

It is noted that other factors that could influence tea production should also be considered in any decision-making context. For instance, this article focuses on the impact of precipitation indices on tea production as this is a key gap in the literature, however it would be valuable to also consider the interactional influences of other meteorological factors such as humidity, sunshine and shade on tea production. In addition, while the pricing of tea according to tea quality is still the basic requirement of the market price mechanism, and raw tea price is always significantly associated with various quality attributes and some of the biochemical parameters [14, 21], there are many complex influencing factors that can affect the pricing of tea [14–17], such as quality, variety, producing area, meteorological factors change, cost of production factors, supply and demand, changes in consumer preferences, policies, market mechanism, etc [14, 17–23, 16, 54], and for a full understanding of the tea industry resilience and year to year variation these factors should also be considered.

Finally, realizing the benefits of our improved understanding will require close engagement between providers of climate information and decision-makers in this tea-growing region. This will help to create a common understanding of the relationship between climate, tea yield and raw tea price. In turn, this will ensure appropriate climate adaptation strategies and policies that maximize benefits to both producers and consumers, and enable robust decision-making in response to existing and new climate information.

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**Data availability statement**

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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