El Niño–Southern Oscillation (ENSO) Impact on Tea Production and Rainfall in South India[✉]

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ABSTRACT

El Niño–Southern Oscillation (ENSO) is an aperiodic oscillation of sea surface temperature (SST)-induced interannual rainfall variability in south India (SI) that has a direct impact on rain-fed agricultural production and the economy of the region. The study analyzed the influence of ENSO-related rainfall variability on crop yield of south Indian tea-growing regions (SITR) for the period of 1971–2015. The relationship between SST anomalies from June to August over the Niño-3 sector of the tropical Pacific Ocean and tea production anomalies of SI shows a positive correlation. However, SST has a negative relationship with rainfall in the regions of the southwest monsoon but not with the northeast monsoon region of the Nilgiris. The correlation between rainfall and crop yield in SI ($r = 0.045$) is positively weak and statistically insignificant ($p > 0.05$). Tea production is influenced more by the cold phase than the warm phase of ENSO, whereas rainfall is greatly influenced by the warm phase. Tea production across the regions indicated that none of the ENSO phase categories based on Niño-3 has significantly greater production than any of the other ENSO phases. Therefore, the predictability of tea production on the basis of ENSO phases is limited. Our findings highlight that the crop production of SITR appeared to be less responsive to the ENSO phases. This may be due to improvements in production technology that mitigated the problems associated with rainfall variability.

1. Introduction

El Niño–Southern Oscillation (ENSO) results from a two-way interaction between the ocean and atmosphere systems in the tropical Pacific Ocean (Trenberth 1997) as a consequence of oscillations in sea surface temperature (SST) of water and associated changes in wind direction. The Southern Oscillation is a crucial source of climate variability at interannual scale that sternly affected the global/regional ecosystems (Jha et al. 2016), rainfall (Chandran et al. 2016; Gill et al. 2017; Son et al.

2016), crop yield (Selvaraju 2003; Padakandla 2016), and food prices (Serra et al. 2011; Ubilava and Holt 2013). The phenomenon involves an aperiodic oscillation of SST between El Niño (warm) and La Niña (cold) from normal phase (Hanley et al. 2003; Chen et al. 2004). Each phase has a well-defined divergent character (Trenberth and Stepaniak 2001) that varies in relative strengths, maturity, seasons of inception and ending, duration, and spatial extent of SST anomaly peaks in the equatorial Pacific Ocean (Lyon and Barnston 2005).

Efforts have been taken to perceive the drives and sources of interannual rainfall variability in the Indian monsoons. Teleconnection of large-scale atmospheric and oceanic circulation features of both preceding and within (Goswami and Xavier 2005; Sahai et al. 2003) the southwest (Webster and Yang 1992; Webster et al. 1998) and northeast monsoons of India (Bhuvaneswari et al.

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2013; Geethalakshmi et al. 2009) is well established in the recent past. The studies have outlined the degree of ENSO-related climate variability on both regional and seasonal scales that is highly dependent on the strength and spatial distribution of the SST anomalies (Goddard et al. 2001). The warm ENSO phase is associated with a weakening and the cold ENSO phase is linked to the strengthening of the southwest monsoon (Rasmusson and Carpenter 1983; Sikka 1980). In contrast, rainfall is higher than normal during the warm phase and lower than normal during the cold phase of the northeast monsoon (Geethalakshmi et al. 2009). The vagaries of irregular southwest monsoon rainfall alone responsible for 72% of the ENSO-related drought (Varikoden et al. 2014) that attends physical manifestations of active and break monsoon conditions resulting in substantial effects on food grain production (Parthasarathy et al. 1992) and gross domestic product of India (Selvaraju 2003). Studies have established the links between ENSO-related interannual climate variability and its influence on agricultural crops (Martinez and Jones 2011) particularly during the warm ENSO phase (Phillips et al. 1998; Meinke et al. 1996; Legler et al. 1999). The observed effects of ENSO on the various crop production system and countries are attributed to the variations in the suitability of agroclimatic elements such as rainfall, temperature, evapotranspiration, soil wetness, and so on that are widely recognized to play a fundamental role in the crop growth and development (Sarma and Lakshmi Kumar 2006).

Inter/intraseasonal variations and extreme weather conditions (e.g., drought) are the enduring challenges of tea cultivation (Raj et al. 2019). India produces 1209 million kg of tea from 563.98 thousand hectares of land and provides annual revenue of ~US\$2514 million (US\$2.08 kg⁻¹ of tea) to Indian tea growers (Tea Board of India 2016). Any unexpected adverse weather conditions may perhaps cause financial hardship to tea growers and 1.25 million dependent laborers who are directly connected with tea cultivation. Although the limited supply of tea could be available despite a brief period of time, the consumer price can rise sharply (Raj et al. 2017). Therefore, understanding the ENSO-related influences on tea production could benefit both growers and consumers of tea. In India, few studies have established the relationship between ENSO and yields of agricultural crop, while the links between tea production and ENSO are yet to be examined systematically. The strong ENSO phases have been found to affect the month and seasonal climatic patterns and thus crop yield (Baigorria et al. 2008; Martinez and Jones 2011), but they are not spatially and temporally uniform across large areas (Ji et al. 2014). Therefore, considering the location-specific quantification

of ENSO-related changes in rainfall, crop yield, and its relationship is important for tea growers and allied industries. The study anticipates that if ENSO-related climate forecasts are available ahead of time it could enable the south Indian (SI) tea growers to mitigate or capitalize possible undesirable consequences of climate variability (Adams et al. 1995). Nevertheless, the usefulness of ENSO-related impact on crop yield for south Indian tea-growing regions (SITR) is yet to be established in detail. Hence, this study critically examines the spatial variability of tea yields and rainfall within ENSO phases and assesses the probable global climate drivers associated with any coherent patterns of variation across the SITR.

2. Data and method

A detailed description of the study area and methods of data collection has been given elsewhere (Raj et al. 2019), and the data are available from the author's repository (Raj 2019). In brief, the SITRs are situated in the Western Ghats of peninsular India and cover three states, Tamil Nadu, Kerala, and Karnataka, longitude ranging from 75.36° to 77.09°E and latitude from 9.57° to 13.35°N, where in fragmented segments or part of the administrative district only tea is cultivated. For the study, rainfall records of four major tea-growing regions are obtained from the meteorological observatory of the United Planters' Association of South India (UPASI) Tea Research Institute and its Regional Centres. The rain gauges are provided by the India Meteorological Department (IMD, Chennai) and the department personnel inspect these gauges and undertake quality control of the data. Historical records of crop yield data of major tea-growing districts of south India for the years 1971–2015 have been collected from the annual reports of the Tea Board, 1981–2005 (Tea Board of India 2016), and J. Thomas & Company Pvt. Ltd. (2013 tea statistics, <http://www.jthomasindia.com>). The study considers an average of total annual rainfall and tea production of only the tea-growing regions in south India. The percentage deviation in crop yield from the trend was calculated as $100 \times (\text{production} - \text{trend})/\text{trend}$. The normalized deviation of the entire time series was calculated using the standard deviation. The Pacific Ocean SST (NOAA_OI_SST_V2) data were obtained from NOAA/OAR/ESRL PSD (NOAA/Physical Sciences Laboratory 2002; Reynolds et al. 2002).

a. ENSO definitions

The study analyzed responses of the crop yield and rainfall to both categorical and continuous measures of

FIG. 1. Relationship between rainfall and tea production: (a) scatter diagram showing the relationship between normalized rainfall and normalized yield and (b) percentage deviation of tea productivity and rainfall with time.

ENSO phases. The spatially averaged Niño-3 SST index of the tropical Pacific Ocean (5°N – 5°S and 90° – 150°W) is derived from the observed data for the period 1971–2015 (NOAA Climate Prediction Center), where the ENSO phase of a year was determined if the 5-month running mean of Niño-3 SST anomalies was $\geq +0.5$ (warm) and ≤ -0.5 (cold) for at least six consecutive months (Trenberth 1997). Of the 45 years, 12 are classified as the warm phase (1972, 1976, 1982, 1986, 1987, 1991, 1997, 2002, 2006, 2009, 2014, and 2015), 9 are classified as the cold phase (1971, 1973, 1974, 1975, 1988, 1998, 1999, 2007, and 2010), and the remaining 24 are classified as the normal years. For conditional forecasting of tea production, ENSO phases were also categorized into warm and cold phase if the Niño-3 SST anomalies were ≥ 0.5 (≤ -0.5) for June–August (JJA).

b. Analysis

The association of normalized annual total rainfall and tea production with JJA SST anomaly over different sectors of the tropical Pacific Ocean was assessed by correlation coefficients. The seasonal lead-lag correlation of the tea production and rainfall was established as a measure of correlation with the Niño-3 SST centered with the JJA (0) season. The percentage deviation of the tea production and rainfall from the trend were compared with the occurrence of ENSO phase of a year based on the standard deviation categories (i) $> +1$, (ii) ± 1 , and (iii) < -1 . To detect the relationships between crop yields and ENSO phase, the deviation categories were further placed into a 3×3 contingency table and χ^2 values were calculated. The differences in the central tendencies of deviation percentage and anomalies of crop production and rainfall for each ENSO phase were also compared using the nonparametric Kruskal–Wallis (KW) H test (Conover 1971).

The anomalies of annual tea production and rainfall were categorized into low, average, and high with the

standard deviation of ± 0.5 as described by Selvaraju (2003). Based on the anomaly categories a plot of the cumulative probability distribution, conditional probability and conditional forecasting tables were prepared for each tea-growing region by ENSO phase.

3. Results

a. Interannual fluctuations in rainfall and tea production

The interannual variability of rainfall and tea production anomalies explains $\sim 22\%$ of variations (Fig. 1a). However, rainfall has a relatively higher magnitude of deviation than tea production (Fig. 1b). During the years of excess rainfall (23 years), the tea production is higher (for 7 years), and during the years of deficit rainfall (22 years), the tea production certainly dropped (for 12 years). The correlation between rainfall and tea production in SI ($r = 0.045$) is positively weak and insignificant at the $p = 0.05$ level (Table 1). However, the rainfall anomalies show an inverse correlation with tea production where only Vandiperiyar ($r = -0.352$) had a significant association with rainfall.

b. Spatial correlation of SST, rainfall, and tea productivity

A positive correlation of SST anomalies over the various sectors of the tropical Pacific Ocean with the tea production of SI is evident from Table 1, except Vandiperiyar. The relationship of tea production with the SST is fairly stronger in the Niño-4 and Niño-3.4 sectors when compared with the Niño-1+2 and Niño-3 sectors. The coefficient of spatial correlation analysis indicates a weak positive association between the rainfall and Niño-4 SST anomalies (Fig. 2b), while tea production anomalies have a relatively strong connection with the Niño-4 and Niño-3.4 regions (Fig. 2a). It is clearly observed that the rainfall over SITR is negatively

TABLE 1. Correlation of annual normalized rainfall, tea productivity (kg ha^{-1}), and Pacific SST anomaly over different sectors of tropical Pacific Ocean (1971 to 2015; $n = 45$). Correlation coefficients of 0.29 and 0.38 are significant at the 5% and 1% levels, respectively.

			Niño-3					
	Rainfall	Niño-1+2	DJF	MAM	JJA	SON	Niño-3.4	Niño-4
Yield								
The Nilgiris	−0.031	0.061	0.098	0.213	0.090	0.044	0.232	0.341
Coimbatore	−0.059	0.059	0.097	0.225	0.051	0.014	0.156	0.244
Munnar	−0.055	0.044	0.007	0.167	0.083	0.016	0.119	0.237
Vandiperiyar	−0.352	0.072	0.057	0.025	−0.101	−0.034	−0.049	−0.164
South India	0.045	0.079	0.092	0.236	0.094	0.046	0.219	0.330
Rainfall								
The Nilgiris		0.191	−0.126	0.074	0.264	0.299	0.230	0.221
Coimbatore		−0.170	0.146	0.004	−0.209	−0.117	0.005	0.102
Munnar		−0.342	−0.108	−0.148	−0.347	−0.312	−0.268	−0.174
Vandiperiyar		−0.085	0.030	0.007	−0.164	−0.225	−0.151	−0.080
South India		−0.205	0.010	−0.042	−0.232	−0.182	−0.100	0.002

correlated (significant at 95% confidence level) with Niño-3 SST besides the Arabian Sea, Bay of Bengal, and east Indian Ocean. Niño-3 SST is positively correlated with the standardized tea production just one season prior (−MAM, where MAM is March–May) to JJA, but not in Coimbatore (Fig. 3a). In all cases except in the Nilgiris, a significantly positive connection between standardized rainfall and Niño-3 SST was found just one season prior to the JJA (Fig. 3b). The SITRs has a significantly positive correlation between standardized tea production and rainfall three seasons prior [SON (−3), where SON is September–November] to the JJA, but Munnar has only one season prior to the current season (Fig. 3c). The correlation of the JJA Niño-3 SST index with the rainfall anomaly has both a positive (in the Nilgiris $r = 0.264$) and a negative (in Vandiperiyar; $r = -0.347$) association. The highest level of correlation was concurrent with the tea productivity of the Nilgiris ($r = 0.341$) and SI ($r = 0.330$) and is significant at $p > 0.05$ when the year considered as an independent sample ($p < 0.01$). Similarly, the highest level of relation coexisted between SON Niño-3 and rainfall of the Nilgiris (0.299) and Munnar ($r = -0.312$). All other regions are insignificantly associated with either tea production or rainfall of the Niño index of various sectors of the seasons.

c. ENSO phases, rainfall, and tea productivity

From Table 2, it was observed that the difference in mean rainfall and crop production of the ENSO phases cannot be generalized among the SITRs. During the warm-phase years, the rainfall declined by 11.38%, and during the cold-phase years, the rainfall increased by 7.16%. Both the warm and cold phases affect the crop yield between 0.97% and 9.56% but not in the cold ENSO phase in Vandiperiyar. Among the regions,

crop yield was maximum during the cold (2316 kg ha^{-1}) and warm (2520 kg ha^{-1}) ENSO phases in Coimbatore, but it is 1.81%–6.19% less when compared with the neutral years. Maximum 12.4% ($\sim 270 \text{ kg ha}^{-1}$) crop loss in terms of productivity was noticed in the Nilgiris during the cold ENSO phase, followed by Coimbatore ($\sim 156 \text{ kg ha}^{-1}$).

From Fig. 4, intraseasonal variation was observed in the crop yield and rainfall with ENSO phases. During the warm phase, crop yield was greater in the months of January by 6.4 kg ha^{-1} , June by 9.0 kg ha^{-1} , July by 16.3 kg ha^{-1} , and August by 2.9 kg ha^{-1} relative to a neutral phase (Fig. 4a). However, a greater yield was observed in January (19.5 kg ha^{-1}), February (22.4 kg ha^{-1}), March (10.9 kg ha^{-1}), June (12.3 kg ha^{-1}), July (11.4 kg ha^{-1}), August (5.3 kg ha^{-1}), September (11.2 kg ha^{-1}), November (5.5 kg ha^{-1}), and December (13.7 kg ha^{-1}) during the cold phase when compared with neutral phase. There was a reduced rainfall during the warm ENSO phase happened in the presummer season [i.e., January (-11.5 mm), February (-21.4 mm), and April (-45.4 mm)] and southwest monsoon [i.e., June (-169.1 mm), July (-102.5 mm), August (-52.8 mm), and September (-57.2 mm)] seasons (Fig. 4b). In contrast, there was increased rainfall during a cold ENSO phase in the month of July (56.6 mm) and October (141.5 mm) when the southwest and north-east monsoons were at their peak. It is interesting to note that the greater rainfall of the warm phase during OND is not helping to increase the crop yield, while increased rainfall during the season of cold phase increased crop yield from the neutral phase. This may be attributed to the fact that the deviation in seasonal rainfall patterns during both the cold and warm ENSO years directly affects the soil moisture and thus tea yield.

FIG. 2. Correlation of average SST (JJA) anomalies with normalized (a) tea production and (b) rainfall of south India.

The percentage deviation of rainfall and tea yield varied with the incidence of ENSO phases (Fig. 5). In 7 of 12 warm ENSO phases, tea production increased between 0.5% and 33.6% and decreased between 5.2% and 26.5% in 5 warm years (Fig. 5a). Tea production decreased in 6 of 9 cold ENSO phases, and in 3 years the crop production increased from mean deviation. In 15 of 24 neutral ENSO phases, tea production increased by 1.3%–24.8% and decreased by from -0.1% to -27.7% in 9 years. The loss of tea production in terms of value during warm ENSO years varied from US\$–15.21 to US\$–1.09 and from US\$–9.29 to US\$–4.32 million during cold-ENSO-phase years from normal years (Fig. 5c). Rainfall is decreased (1.5%–33.4%) in 8 of 12 warm-phase years

in which 5 years are El Niño drought years (if the percentage of departure is less than 10% during the warm phase) and 3 are non-El Niño drought years (Fig. 5b). Of 4 in 9 cold phases, 2 years each are La Niña drought (1973 and 1988) and La Niña flood (1975 and 2007) years (if the percentage of departure is more than +10% during the cold phase). Rainfall is decreased in 9 of 24 neutral years in which 5 years are neutral drought years and 8 are neutral flood years. There is no specific pattern in cold or warm following neutral years, cold following warm years, or vice versa having a higher or lower trend in rainfall or tea production.

The three-by-three contingency table and χ^2 relationship (Table 3) show that the ratio of the above to

FIG. 3. The seasonal lead-lag correlation of the Niño-3 SST with (a) tea yield or (b) rainfall and (c) between tea yield and rainfall centered with JJA (0) season.

below trend during the warm ENSO phase is 2:2 and during the cold ENSO phase is 1:4 in both south India and in the Nilgiris. The tea production in Coimbatore ($\chi^2 = 11.64$) is significantly altered ($p < 0.05$) by ENSO extremes, whereas it is not significantly affected by the ENSO extremes of all other regions. The ratio of above trend to below trend during warm ENSO phase years for rainfall is 0:4 (Munnar), 0:3 (south India), and 5:1 (the Nilgiris), and these regions are significantly altered ($p < 0.1$) by ENSO extremes with χ^2 values of 8.013, 9.463, and 7.605, respectively.

d. Ability to predict tea production and rainfall under ENSO phases

To find the prediction skill, the mean percentage deviations of tea production and rainfall anomalies under different ENSO phases were analyzed and compared

with the KW H test (Table 4). The value of H is significant at the 5% level of rainfall of Munnar ($H = 6.103$), which indicates that at least one of the Niño-3 ENSO phases has significantly greater rainfall than at least one other of the ENSO phases and reveals good predictability of the region. During the warm ENSO phase year, on average, the rainfall decreased by 22.5 cm (-7.81%), and during the cold ENSO phase, it decreased by 1.02 cm (-0.36%) from a normal year. The mean value of the Nilgiris annual rainfall under cold ENSO phases was significantly different ($p < 0.10$) from the warm years. Although annual rainfall increased during cold ENSO phase years above that of warm ENSO phase years in Munnar and Vandiperiyar, it was not significant. However, rainfall during a warm ENSO phase was significantly different from a neutral ENSO phase in Coimbatore, Munnar, and south India. Tea production across the regions and between the ENSO phases indicates that none of the Niño-3 ENSO phases have significantly greater production than at any other of the ENSO phases. Therefore, predictability in tea production based on the ENSO phases is limited. The average increase of tea production of south India during a warm ENSO phase year is 5.17×10^3 t (1.43%). In a cold ENSO phase year, the average production reduction is -15.0×10^3 t (-8.37%). Although tea production increased during warm ENSO phase years of the Nilgiris (1.34×10^3 t) and Coimbatore (0.71×10^3 t) and the cold ENSO phase in Vandiperiyar (1.69×10^3 t) is above that of normal, it was not significant.

e. Probabilistic forecasting of tea production

Normalized tea production associated with ENSO phases showed that (Fig. 6) the crop production anomalies were lower with cold ENSO phase than warm and neutral ENSO phases at any probability level except at Vandiperiyar (Fig. 6d). The probability of exceeding above-normal tea production anomalies is a minimum of 20% to a maximum of $<50\%$ in a warm ENSO phase year, whereas there is no probability of exceeding above-normal tea production during a cold ENSO phase year (Figs. 6a–c,e). The cumulative distribution function during cold and warm ENSO phase years has shown that there are $\sim 40\%$ and 65% probability of positive tea values, respectively (Fig. 7a). The relationship between the Niño-3 SST (JJA) versus the changes in the anomalies of tea value is highly significant ($r = 0.52$, $n = 43$, and $p < 0.01$; Fig. 7b), and the Niño-3 SST is responsible for 42.8% of the variability of tea value.

Table 5 showed the conditional probabilities of tea production and rainfall levels under different annual Niño-3 SST categories were related to JJA Niño-3 SST. Irrespective of ENSO phases, the prospects of getting

TABLE 2. Annual yield and rainfall characteristics of the study location under warm (W), cold (C), and neutral (N) ENSO phases (1971–2015). Values inside the parentheses are the difference in percentage.

	The Nilgiris	Coimbatore	Munnar	Vandiperiyar	South India
Yield					
Cold	1891 ± 452	2319 ± 469	2042 ± 428	2111 ± 278	1742 ± 356
Warm	2161 ± 486	2475 ± 320	2112 ± 359	2043 ± 209	1928 ± 315
Neutral	2176 ± 387	2520 ± 320	2150 ± 359	2057 ± 236	1947 ± 231
C–N	–269.9 (12.4)	–155.9 (6.19)	–70.3 (3.42)	67.4 (3.28)	–186.2 (9.56)
W–N	–15.12 (0.69)	–45.70 (1.81)	–38.22 (1.78)	–13.34 (0.65)	–18.97 (0.97)
Rainfall					
Cold	1658 ± 195	3812 ± 490	4093 ± 545	1923 ± 326	2871 ± 261
Warm	1869 ± 343	3505 ± 500	3690 ± 647	1563 ± 489	2657 ± 384
Neutral	1811 ± 368	4034 ± 979	4269 ± 687	1878 ± 423	2998 ± 449
C–N	–210.2 (11.6)	306.6 (7.60)	403.0 (9.44)	359.7 (19.15)	214.8 (7.16)
W–N	57.91 (3.20)	–529.0 (13.11)	–579.4 (13.57)	–314.9 (16.77)	–341.3 (11.38)

either lower or higher tea production during any given year are 14% and 38%, respectively. Based on annual SST anomalies, there is an equal probability of getting higher and lower (30%) tea production during warm ENSO phase, while higher tea production drops to 8% and low production increases to 50% for cold ENSO phase. Similarly, the probability of higher production drops to zero and low production increases to 56%–60% for cold and warm JJA SST categories. Without taking account of the ENSO information, the chance of lower or higher rainfall during any given year is 15% and 46% and 29% and 38%, respectively, observed in annual and seasonal SST categories (JJA Niño-3). During both cold and warm ENSO phases, the probability of higher rainfall drops to 33% and 20% and for low production; it increases to 50% and 40% for annual SST, while it is 44% and 40% in JJA SST categories. Table 6 presented the predictions based on conditional probabilities with SST categories by observed tea production and rainfall. According to the conditional probabilities, the prediction for the two warm ENSO years, 2009 and 2014, was high and average tea production, respectively. The

prediction for the most probable drought (warm ENSO) years was average rainfall, while during cold ENSO years, 2007 and 2010 were average and high rainfall, respectively.

4. Discussion

This study explored the association of tea production and rainfall anomalies of major tea-growing regions of SI with the ENSO phases using various statistical approaches. The reduced tea yield during the cold phase is larger and more consistent than the yield decrease during the warm phase (Table 2). The overall association of crop yield with ENSO is insignificant (Table 4); this may be caused by the higher-than-normal rainfall during October–December of the warm and cold ENSO phases (Fig. 4b). The result further supported by the lead–lag correlation between tea production and rainfall (Fig. 3c) is significantly positive with the preceding two seasons. During the drought months of December–February (DJF) (and in some years even up to March and April), the enhanced rainfall influenced extended

FIG. 4. The average monthly (a) tea productivity and (b) rainfall of tea-growing regions of south India under ENSO phases (1971–2015).

FIG. 5. Percentage deviation of (a) tea yield anomalies and (b) rainfall anomalies, and (c) value of tea production in U.S. dollars under ENSO phases (1971–2015).

soil moisture and groundwater recharge, which are important factors determining sustainability of tea yields. Considering monthly crop yield, there is an inverse or lead–lag relationship between yield [April–June (AMJ)] and rainfall (JJA) that is attributed to the other cofactors related to increasing rainfall such as higher cloudiness, fewer sunshine hours, and higher relative humidity, which leads to physiological limitations of the tea plant, specifically, photosynthesis.

Although above trends and below trends in tea production have occurred under different ENSO phases, crop yield does not show any association with ENSO phase (except in Coimbatore), as indicated by the lack of significance (Table 3). Because tea is a perennial plantation crop of C3 metabolism, it is well adapted to

various climatic conditions (specifically by enhanced adaptive stomatal regulation) for more than 100 years of lifetime established by a well-deep rooting system. Hence, ENSO-related drought may not considerably affect the tea plants/plantation as much as they do other annual agricultural crops. However, the enhanced rainfall during cold ENSO phase may increase leaf wetness, which favors the manifestation of the devastating leaf diseases, gray (*Pestalotiopsis theae*) and blister blight (*Exobasidium vexans*), resulting in drops (17%–35%) in yields (Jamieson et al. 2012), functional quality, and thus price realization of tea (Ahmed et al. 2014; Muthumani et al. 2013). The experimental evidence shows that extreme rainfall events offset the functional quality of tea by reducing the concentrations of polyphenolic catechins and methyl-xanthine secondary metabolites and thus reducing the vending price and export of tea (Adams et al. 1995; Jeyaramraja et al. 2003; Kottur et al. 2010).

Above-normal rainfall in cold ENSO phase also has an indirect influence on the crop yield because its association with low daytime air temperatures and solar radiation (Anandacoomaraswamy 2000; Carr and Stephens 2011) may translate into reduced CO₂ assimilation and delayed crop development, that is, leaf expansion time (Carr 1972). Meanwhile, the increased intensity of rainfall in a shorter period could result in more run-off, decreased water percolation, and thus lesser available water in the soil (Beran and Arnell 1989). The regions receiving increased rainfall during the cold phase would lead to leaching of fertilizer and reduction of soil fertility finally result in a poor-quality harvest (Carr and Stephens 2011). The diminishing effects of high rainfall anomalies during cold phase indicate that there is an opportunity for yield increases during warm phase through increased inputs. For instance, if the effects of a warm ENSO event on crop yields will become more marked in the future, the optimistic usage of fertilizers and other agriculture technological advances may allow farmers to capitalize on a warm ENSO event.

The crop yield anomalies are positively correlated with Niño-3 SST anomalies. Just one preceding season is almost insignificant, indicating that there is no lag-predictive power of observed Niño-3 SST during the preceding spring (MAM) and winter (DJF). However, there is a highly significant association between rainfall in the tea-growing regions of SI and Niño-3 SST just one season prior to JJA, except the Nilgiris, which is the region that receives maximum rainfall during the northeast monsoon showed a significant positive association two seasons prior to (–DJF) JJA. The sliding correlation between rainfall and tea production is inconsistent and varies among the regions. The results of season-lagged

TABLE 3. Contingency table describing the frequency of years under categories of annual tea production and rainfall in warm (*W*), cold (*C*) and neutral (*N*) ENSO years (1971–2015). Sig indicates significance, with boldface type indicating at the 10% level or better; SD is standard deviation.

Regions	Tea production (kg ha ⁻¹)						Rainfall (mm yr ⁻¹)					
	<i>C</i>	<i>W</i>	<i>N</i>	Total	χ^2	Sig	<i>C</i>	<i>W</i>	<i>N</i>	Total	χ^2	Sig
The Nilgiris												
Above trend	1	2	4	7	5.872	0.209	0	5	3	8	7.605	0.100
At trend (± 1 SD)	4	8	18	30			7	6	15	28		
Below trend	4	2	2	8			2	1	6	9		
Coimbatore												
Above trend	2	3	2	7	11.64	0.020	1	0	6	7	4.355	0.360
At trend (± 1 SD)	3	7	21	31			7	10	14	31		
Below trend	4	2	1	7			1	2	4	7		
Munnar												
Above trend	2	2	3	7	1.377	0.848	1	0	6	7	8.013	0.091
At trend (± 1 SD)	4	7	16	27			8	8	15	31		
Below trend	3	3	5	11			0	4	3	7		
Vandiperiyar												
Above trend	2	1	3	6	0.971	0.914	2	1	6	9	5.453	0.244
At trend (± 1 SD)	5	8	16	29			7	7	15	29		
Below trend	2	3	5	10			0	4	3	7		
South India												
Above trend	1	2	2	5	6.750	0.150	0	0	6	6	9.463	0.051
At trend (± 1 SD)	4	8	20	32			9	9	16	34		
Below trend	4	2	2	8			0	3	2	5		

correlation confirmed that the SST has no lag-predictive value of tea production of the SI, while we could lag predict rainfall with SST of one preceding season, but for the Nilgiris we needed SST of the two preceding seasons.

The cumulative distributions of normalized tea production under different ENSO phases have shown that the crop yield of warm and neutral phases shifts either positively or negatively from the neutral distribution, but cold phase greatly reduces the crop yield, except in Vandiperiyar (Figs. 6a–e). The trend of reduced crop

yield in cold phase has strongly reflected on tea value (Fig. 7a). The cold phase has a great positive shift in the cumulative distribution of tea value when compared to the neutral phase; on the other hand, a warm phase greatly reduces the tea value. The increase in tea value during the cold phase and decrease during the warm phase are attributed to increases in demand for tea in the market because of lower production as influenced by ENSO-related events. The conditional probability framework predicted the average tea production for

TABLE 4. Kruskal–Wallis nonparametric independent *H* test using mean percentage deviation (first number in the cell) of annual tea production (kg ha⁻¹) and rainfall (cm) from normal under warm (*W*), cold (*C*) and neutral (*N*) ENSO phases for the period from 1971 to 2015, with sample *n* = 45. The values in parentheses are the actual yield (kg ha⁻¹) and rainfall (cm) deviations. Asterisks give the level of significance, with two asterisks indicating the 5% level and one asterisk indicating the 10% level, and NS indicates not significant.

	<i>C</i>	<i>W</i>	<i>N</i>	KW <i>H</i>	<i>C</i> – <i>W</i>	<i>C</i> – <i>N</i>	<i>W</i> – <i>N</i>
Crop							
The Nilgiris	–10.6 (–3.88)	2.17 (1.34)	2.89 (0.79)	1.931 ^{NS}	NS	NS	NS
Coimbatore	–6.04 (–2.05)	0.28 (0.71)	2.13 (0.49)	0.405 ^{NS}	NS	NS	NS
Munnar	–3.62 (–3.78)	–0.30 (–1.30)	1.51 (0.77)	0.530 ^{NS}	NS	NS	NS
Vandiperiyar	2.27 (1.69)	–1.00 (–0.58)	–0.35 (–0.34)	1.285 ^{NS}	NS	NS	NS
South India	–8.37 (–15.0)	1.43 (5.17)	2.43 (3.04)	1.759 ^{NS}	NS	NS	NS
Rainfall							
The Nilgiris	–7.65 (–13.73)	4.06 (7.29)	0.84 (0.08)	3.479 ^{NS}	*	NS	NS
Coimbatore	–0.96 (–3.68)	–8.92 (–34.3)	4.82 (0.48)	3.451 ^{NS}	NS	NS	*
Munnar	0.33 (1.34)	–9.55 (–39.0)	4.65 (0.47)	6.103 ^{**}	NS	NS	**
Vandiperiyar	6.64 (12.0)	–13.3 (–24.0)	4.16 (0.42)	2.737 ^{NS}	NS	NS	NS
South India	–0.36 (–1.02)	–7.81 (–22.5)	4.04 (0.40)	4.155 ^{NS}	NS	NS	*

FIG. 6. Cumulative frequency distribution of standardized tea production during warm, cold, and neutral ENSO phases for (a) the Nilgiris, (b) Coimbatore, (c) Munnar, (d) Vandiperiyar, and (e) south India.

most of the year, though there are variations in the rainfall category. The result revealed that the impact of tea production would not be affected more severely if the monsoon enters into a critical phase.

The tea production followed by severe and prolonged ENSO events such as those in 1982 and 1997 exhibited dissimilar responses between the regions (Figs. S1a–d in the online supplemental material). During a strong warm phase during 1982 in the Pacific Ocean, the yield of SI showed below-normal levels (-8.9%), except as a slight increase in Vandiperiyar (2.2%). In contrast, the

strong warm phase during 1997 resulted in enhanced production (22%) in all the tea-growing regions. This inconsistent pattern in tea production demonstrates that both higher and lower yields have occurred during the warm and cold ENSO phases; therefore, ENSO alone cannot completely explain the interannual variability of tea production in the SITRs. The variance in regional response to two very strong ENSO phases further illustrates the difficulty in predicting extratropical response to ocean–atmosphere interactions in the tropical Pacific Ocean. The study also recognizes that there are many other ENSO-related

FIG. 7. Impact of ENSO phases on the value of tea production: (a) cumulative frequency distribution of the tea value in millions of U.S. dollars, and (b) relation between the value of tea production and average Niño-3 SST (JJA).

climate factors can have an indirect but important effect on crop yield of tea, largely through coexisting effects on other physical systems as revealed in Florida winter vegetable yields response to ENSO (Hansen and Jones 1999).

In contrast to the yield, a drop in rainfall during the warm phase is larger than the cold phase and significantly differed from a neutral phase in Coimbatore, Munnar, and south India (Table 4). A decrease in rainfall during the cold phase observed in the Nilgiris (11.6%) was found to be significant from the warm phase. The frequency of above-/below-trend rainfall of the Nilgiris, Munnar, and south India showed a significant difference (Table 3; $p < 0.1$) with ENSO. Based on the rainfall distribution, drought years (rainfall deviation below -10%) were observed in all the ENSO phases (online supplemental Fig. S1). More of the ENSO-related drought conditions in the rainfall of SI are associated with strong warm phases (5 of the 12 years), indicating that about 42% of the drought years are associated with Pacific influence. However, the association varied between the regions, ranging from 50% (in Coimbatore, Munnar, and Vandiperiyar) to 25% (in the Nilgiris).

A positive and negative correlation of rainfall over the tea-growing regions of SI with Niño-3 SST is dependent on the region when the major seasonal rainfall occurs. Region-specific correlation of rainfall on JJA Niño-3 SST (Fig. S2 in the online supplemental material) showed that the region receiving higher rainfall during the northeast monsoon shows a significant negative relationship (the Nilgiris; Fig. S2a), and the regions receiving higher rainfall during the southwest monsoon exhibit a positive relationship (Figs. S2b–d). The contrasting correlation pattern of both the monsoon and its mechanisms during ENSO phase have been documented by many authors (Bhuvaneswari et al. 2013;

Geethalakshmi et al. 2009; Gregory 1989). The results exhibited that the northeast monsoon of the Nilgiris had the highest positive correlation with Niño-3 SST for the months of JJA and SON, indicating that, whenever there is raised SST in the Niño-3 region, there is an increase in rainfall of northeast monsoon, and vice versa. A drop in crop production by -8.37% during the cold ENSO phase is the major impact of climate variability on south Indian tea production. A warm ENSO phase could increase the tea production by 1.43%, whereas a neutral ENSO phase can increase tea production by 2.4% from the long-term trend.

The normal or below-normal rainfall during warm-phase years in most of the tea-growing regions may be due to the conducive conditions for the westward-propagating Rossby waves in the eastern-central Pacific generated after collapsing the Kelvin–Rossby wave packet as part of the eastward-propagating Madden–Julian oscillation (MJO) (Wang and Xie 1997). During El Niño years, the eastern Pacific is warm and therefore conducive to the eastward propagation of MJO.

TABLE 5. Conditional probability of SI tea production and rainfall under the annual and JJA Niño-3 SST categories based on the observations for the period from 1971 to 2015.

SST category	Tea production			Rainfall		
	Low	Avg	High	Low	Avg	High
Annual SST						
Cold	0.50	0.42	0.08	0.50	0.17	0.33
Neutral	0.15	0.54	0.31	0.15	0.38	0.46
Warm	0.30	0.40	0.30	0.40	0.40	0.20
JJA SST						
Cold	0.56	0.44	0	0.44	0.22	0.33
Neutral	0.14	0.48	0.38	0.29	0.33	0.38
Warm	0.60	0.40	0	0.40	0.40	0.20

TABLE 6. Conditional forecasting of the tea production, based on the Niño-3 SST and comparison with observed tea productivity at study locations.

Year	Annual SST	JJA SST	Obs SI tea production		Obs rainfall	
			Normalized	Category	Normalized	Category
2001	Neutral	Neutral	−0.15	Average	0.32	Average
2002	Warm	Neutral	−0.36	Average	−1.41	Low
2003	Neutral	Neutral	0.19	Average	−1.57	Low
2004	Neutral	Neutral	−0.25	Average	2.31	High
2005	Neutral	Neutral	−0.05	Average	1.17	High
2006	Neutral	Neutral	0.23	Average	−0.29	Average
2007	Cold	Cold	−0.33	Average	0.73	High
2008	Neutral	Neutral	0.51	High	−0.45	Average
2009	Warm	Warm	0.59	High	0.09	Average
2010	Cold	Cold	0.25	Average	−0.17	Average
2011	Cold	Neutral	0.32	Average	0.52	High
2012	Neutral	Neutral	0.23	Average	−1.86	Low
2013	Neutral	Cold	0.18	Average	1.65	High
2014	Warm	Neutral	0.41	Average	0.75	High
2015	Warm	Warm	0.10	Average	−0.11	Average

However, during normal years, the eastern Pacific SST is colder or normal and therefore, the eastward-propagating Kelvin–Rossby wave packets suddenly collapse over the east-central Pacific, and thus it generates strong westward-propagating Rossby wave through the 10°–20°N latitude band. The conduciveness in the central-eastern Pacific may be the key reason for the strong variance of intraseasonal oscillation during normal drought years.

5. Conclusions

The overall results of the study revealed that tea production in SI as a single entity is less responsive to ENSO phases. However, the various influences of ENSO on tea production among the tea-growing regions are associated with differences in monsoon pattern, water availability, topography, microclimate, and soil type. Furthermore, the factors other than rainfall more relevant for the crop are air temperature, relative humidity, solar radiation, evapotranspiration, and so on, and these may influence crop growth and development. However, the association between ENSO and this climatic variable has not been documented in the study or tea-growing regions of SI so far. The results of this study provide evidence that the relationship of SST to rainfall has some predictability, even before the start of the monsoon. This is a necessary but not sufficient condition for farm and policy applications of long-lead climate forecasts (Hansen 2002). Exploiting this predictability will require further work with refined predictors and prediction systems, higher-resolution crop and rainfall data, and perhaps process-level models of crop response. The results also indicate, at the coarse region level, which tea production regions show the greatest sensitivity to the

predictable components of monsoon rainfall. This analysis, at a finer spatial scale, could provide further information for targeting interventions.

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