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ORIGINAL PAPER

Climate-based statistical regression models for crop yield forecasting of coffee in humid tropical Kerala, India

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Abstract A study on the variability of coffee yield of both *Coffea arabica* and *Coffea canephora* as influenced by climate parameters (rainfall (RF), maximum temperature (Tmax), minimum temperature (Tmin), and mean relative humidity (RH)) was undertaken at Regional Coffee Research Station, Chundale, Wayanad, Kerala State, India. The result on the coffee yield data of 30 years (1980 to 2009) revealed that the yield of coffee is fluctuating with the variations in climatic parameters. Among the species, productivity was higher for *C. canephora* coffee than *C. arabica* in most of the years. Maximum yield of *C. canephora* (2040 kg ha^{-1}) was recorded in 2003–2004 and there was declining trend of yield noticed in the recent years. Similarly, the maximum yield of *C. arabica* (1745 kg ha^{-1}) was recorded in 1988–1989 and decreased yield was noticed in the subsequent years till 1997–1998 due to year to year variability in climate. The highest correlation coefficient was found between the yield of *C. arabica* coffee and maximum temperature during January (0.7) and between *C. arabica* coffee yield and RH during July (0.4). Yield of *C. canephora* coffee had highest correlation with maximum temperature, RH and rainfall during February. Statistical regression model between selected climatic parameters and yield of *C. arabica* and *C. canephora* coffee was developed to forecast the yield of coffee in Wayanad district in Kerala. The model was validated for years 2010, 2011, and 2012 with the coffee yield data obtained during the years and the prediction was found to be good.

Keywords Coffee yield · Variability · Climate · Statistical model

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Introduction

Coffee crop is the second most traded commodity in the world, second only to the oil production chain. The genus *Coffea* has more than 124 species, among which *Coffea arabica* L. and *Coffea canephora* Pierre ex A. Froehner (Davis et al. 2012) are responsible for the yield of about 99 % of traded coffee bean. In recent years, the global production of coffee surpassed 141 million (60 kg) bags (International Coffee Organization 2015). It generates 100, 000 million USD year^{-1} and constitutes the social and economic basis of many tropical developing countries.

In India, coffee is an important plantation crop, which is mainly cultivated in the Southern States (Karnataka, Kerala, and Tamil Nadu) and to a lesser extent, in non-traditional areas like Andhra Pradesh, Orissa, and Northeastern Indian States. The major coffee-growing areas are the districts of Chickmagalur, Coorg, and Hassan in Karnataka, Wayanad, Idukki, and Palakad (Nelliampathys) in Kerala and Dindigul (Pulneys), Salem (Shevroys), Coimbatore (Anamalais), and Nilgiris in Tamil Nadu (Achoth 2005). Commercially important species of coffee, viz., both *C. arabica* and *C. canephora* species of coffee are cultivated in India. Kerala is the second largest producer of coffee in India. It produces 21 % of the total coffee output of the country. In Kerala, Wayanad is the leading coffee producing district, which produces more than

80 % of the total coffee production from the State. However, it is interesting to note in the Coffee bowl of Kerala (Wayanad district) majority of the area falls under *C. canephora* and *C. arabica* coffee is only marginally cultivated.

Rainfall is required for the growth of all plantation crops. The months of February to March are when the first showers for the year are received. For the coffee farmer, these first showers are indeed referred to as blossom showers and rainfall received during April and May is known as backing showers/ rains (Coffee Board 2009). Temperature and rainfall are the major climatic parameters that determine the yield of coffee crop (International Trade Centre 2010).

Climate change is recognized to be one of the most serious challenges facing humankind nowadays. Even though, there is vigorous debate on global warming (Kerr 2009; Solomon et al. 2009), mean global temperature has increased by 0.8 °C since 1880 and may increase by an additional 3 to 7 °C by 2100 under business as usual scenario (IPCC 2007a, b; Allen et al. 2009). With respect to Kerala also, similar trend was observed and the increase in annual average temperature was 0.44 °C (Rao et al. 2009). In another study at Centre for Water Resources Development and Management (CWRDM), Kozhikode, Kerala, in which the maximum temperature rose to the tune of 0.6 °C during winter and 0.55 °C during summer between 1983 and 2010 (Joseph et al. 2011; Surendran et al. 2014). These studies confirmed that climate change and climate variability have become a reality.

The change of climate variables, either promoted by natural causes, or by human action, occurring alone or concomitantly, strongly limits agricultural yields and quality. Both low and high temperatures are quite relevant, as they contribute to large yield decreases (often above 50 %) in many crops (Chaves et al. 2003; Wang et al. 2003). Any pragmatic crop planning needs a thorough understanding of the climate and in particular, the rainfall (its variability in the amount, distribution of occurrence), temperature, and evaporative demand.

Climatic variability has always been the main factor responsible for the fluctuation of coffee yields in the world (http://www.ico.org/sustaindeve.asp). Climate change, as a result of global warming, is expected to result in actual shifts on where and how coffee may be produced in future (International Trade Centre 2010). Temperature and rainfall conditions are the main drivers when it comes to yield, i.e., production. In this respect, the two main species, *C. arabica* and *C. canephora* that together account for about 99 % of world production have different requirements.

Due to different evolutionary history, the temperature requirements of *C. arabica* and *C. canephora* are somewhat different. Moreover, in many tropical countries these species have been cultivated under full sun conditions, despite their origin in shaded habitats (DaMatta 2004), what alters the temperature values to which the plants are exposed. In fact, coffee species are usually susceptible to cold conditions, what limits their geographical distribution if monthly average temperatures are below 15–16 °C (Barros et al. 1997).

Temperature, rainfall, sunlight, wind, and soils are all important for the better growth and development, but requirements vary according to the species as mentioned earlier. Ideal average temperatures range between 15 to 24 °C for *C. arabica* coffee and 22 to 32 °C for *C. canephora* which can flourish in hotter, drier conditions but does not tolerate temperatures much below 15 °C, as *C. arabica* can tolerate for short periods (Table 1). In general, coffee needs an annual rainfall of 1500 to 3000 mm, with *C. arabica* needing less than other species. The pattern of rainy and dry periods is important for growth, budding, and flowering. Rainfall requirements depend on the retention properties of the soil, atmospheric humidity and cloud cover, as well as cultivation practices.

Table 1 Climatic requirement for *C. arabica* and *C. canephora* (*Robusta*) coffee under Indian conditions

Climatic	Arabica				Robusta			
	HS	MS	MAS	NS	HS	MS	MAS	NS
Mean temperature regime in °C	20–24	15–19; 25–26	12–13; 27–28	<12; >28	22–32	20–21	18–19	<18
Minimum temperature of coldest month in °C	>10	9–10	7–8	<7	>10	9–10	7–8	<7
Mean relative humidity %	70–90	60–70	>90	<60	70–95	60–70: >95	50–60	<50
Elevation M (above MSL)	800–1500	700–800; 1500–1800	300–700; 1800–2000	<300; >2000	200–1000	100–200; 1000–1200	<100; 1200–1400	>1400
Total rainfall in mm	>1100	1000–1100	800–1000	<800	>1250	1000–1250	950–1000	<950
Rainfall March–April in mm	30–40	25–30	15–25	<15; >40	30–40	25–30	15–25	<15; >40
Rainfall during April–May in mm	65–75	50–65	25–50	<25	65–75	50–65	25–50	<25
Rainfall during June–July in mm	>200	100–200	50–100	<50	>200	100–200	50–100	<50

HS highly suitable, *MS* moderately suitable, *MAS* marginally suitable, *NS* not suitable, *Above MSL* above mean sea level in M

Whereas *C. canephora* coffee can be grown between sea level and about 800 m, *C. arabica* does best at higher altitudes and is often grown in hilly areas. As altitude relates to temperature, *C. arabica* can be grown at lower levels further from the equator, until limited by frost (Gopakumar 2011).

The use of climate-based statistical regression models (agro-meteorological models) that monitor the effects of climate during the critical growth stages of the coffee is important for crop yield estimate methods. Crop yield involves several factors as inputs, technical advances, biological, and climatic, in which the latter is fundamental and can be well characterized by agro-meteorological models. The climate variables like rainfall, maximum and minimum temperature, relative humidity, and sunshine hours affect crop growth and development in different ways and at different times of growth cycle of the crop. The relationship between crop yield and climatic parameters can be identified with the help of multiple regression models (Agrawal et al. 2001). Statistical model developed using past climate and yield data will help to determine the impact of climate on coffee berry production and also it will help to forecast coffee berry yield for the future. Coffee Board of India presently utilize coffee production estimates during blossom and post blossom stages to forecast the coffee production. The yield surveys are extensive, as plot yield data are being collected under scientifically designed complex sampling design that is based on a stratified multistage random sampling (Ghosh et al. 2014). However, climate based yield forecast models are using different statistical approaches to forecast the crop yield well before harvest of the crop for several food and cash crops in India (Tripathy et al. 2012; Paul et al. 2012). Many studies have been conducted in Brazil linking the climatic parameters on coffee growth, yield and even there were some studies which describes the development of models for predicting the coffee yield using agro-meteorological data or using remote-sensing approaches (Weill 1990; Carvalho et al. 2003; Camargo et al. 2003; Davis et al. 2012; Partelli et al. 2014). However, such studies are rare for coffee in India. Hence, an attempt has been made in the present paper, to develop a statistical regression model for forecasting coffee yield in Wayanad, Kerala, based on rainfall and temperature and also to validate the same with the actual yield data. This will help the planners to predict the coffee yield in a more precise manner, under the changing climate scenario.

Data and methodology

Study site

Wayanad is conventional coffee-growing district of Kerala State. Regional Coffee Research Station, Chundale, Wayanad, is situated at an elevation ranging from 700 to 2100 m above MSL. Wayanad lies between 11° 27′ and 15° 58′ north latitude and 75° 47′ and 70° 27′ east longitudes. The high elevation and the amount of forest cover exist create a pleasant climate in the region. Generally, the year is divided in to four seasons; cold weather (December to February), hot weather (March to May), southwest monsoon (June to September) and northeast monsoon (October to November). During the hot weather, the temperature goes to maximum 30.3 °C, and during the cold season, temperature goes down to 16.4 °C. The average annual rainfall is around 2800 mm and for the study period (30 years) it was found to be 2864 mm. Mean monthly climate parameters (1980–2009) at Chundale is given in Table 2.

The study site is situated inside the Regional Coffee Research Station (RCRS), Chundale in Wayanad district of Kerala and it was established primarily to develop appropriate coffee production technologies to suit the region where *C. canephora* is the dominant crop. The station covers an area of 116 ha (290 acres) with 30 ha (74 acres) of farm with an adequate laboratory support for research. The coffee plantations consist of *C. arabica* and *C. canephora* with an average age of 40 to 50 years old. All agronomic management operations were followed as per the crop production guide of Coffee board. The soil pH varies from 5.2–6.3. Organic carbon content is medium and phosphorus and potassium is low to medium.

Coffee species

Commercially important species of coffee, viz., both *C. arabica* and *C. canephora* species of coffee are cultivated in India. Due to different evolutionary history, the temperature requirements of *C. arabica* and *C. canephora* (*Robusta*) are somewhat different. Hence, initially climatic requirement for both the species were gathered from existing literature and presented in Table 1. The earlier studies showed that both the species do not tolerate temperatures much below 10 °C.

Table 2 Climate of Wayanad (1980–2009)

Month	Tmax	Tmin	RH	Rainfall
January	28.8	16.8	80.5	11.8
February	29.8	18.2	78.8	10.4
March	24.9	19.6	78.6	37.1
April	26.4	20.3	81.4	112.9
May	30.3	20.4	83.7	153.3
June	26.2	19.7	89.4	633.9
July	24.5	19.3	91.6	797.1
August	24.8	19.4	90.5	510.3
September	26.7	19.5	86.3	211.6
October	27.1	19.2	86.5	258.5
November	27.4	18.7	85.5	95.5
December	27.9	16.4	82.4	29.2
Mean	27.1	19.0	84.6	2861.4

C. canephora can grow well in mean temperatures range between 22 to 32 °C, whereas for *C. arabica* coffee it is 15 to 24 °C and this indicate that *C. canephora* requires little hotter and drier climate. In general, coffee needs an annual rainfall of 1500 to 3000 mm, with *C. arabica* needing less than *C. canephora*. With respect to elevation, *C. canephora* coffee can be grown at the height of 200 to 1000 m above mean sea level (MSL) and, *C. arabica* does best at higher altitudes i.e., 800 to 1500 m and is often grown in hilly areas.

Data collection

Agro-meteorological observatory is established in 1973 and is located within the research farm mentioned earlier in "Study site" section. Yield data of coffee for 30 years (1980–2009) were collected (yield data collection started after 10–15 years of coffee age) from plantations of *C. arabica* and *C. canephora* and data on climate parameters for the study period (maximum and minimum temperature (°C), relative humidity (%), and rainfall (mm)) were collected from the agro-meteorological observatory of this site.

Statistical analysis

Student's "*t*" test was applied to test the statistical significance (Fisher and Yates 1938) of correlation. To find out the climatic parameters mostly influencing the coffee yield, the average monthly maximum, minimum temperature, RH and rainfall for months prior to harvesting were correlated with yield for the corresponding year. For model development, the entire data set have been used for the correlation purposes. However, the highest positively correlated data only used for the development of regression model expecting that it will give closer values for predicted and observed values. The statistically significant parameters were selected and all were subjected to stepwise multiple regression using SPSS software, version 15.0 developed by IBM, Bangalore, India (International Business Machines Corporation 2013). A regression model was developed using the climatic parameters.

For model validation, 3-year temperature and humidity data (2010–2011, 2011–2012, and 2012–2013) were taken and substituted in the regression equation and the yield of coffee for those years were predicted. These predicted yields were compared with the observed yield data.

Results and discussion

Climate parameters

Trend analysis of climate parameters done for Chundale indicated that the maximum temperature showed increasing trend between 1990 and 2009. Similar observation was noticed for minimum temperature and rainfall (Fig. 1). Overall increase in annual average temperature was 0.44 °C. This confirmed the similar trend observed in other parts of Kerala (Joseph et al. 2011; Gopakumar 2011; Surendran et al. 2014).

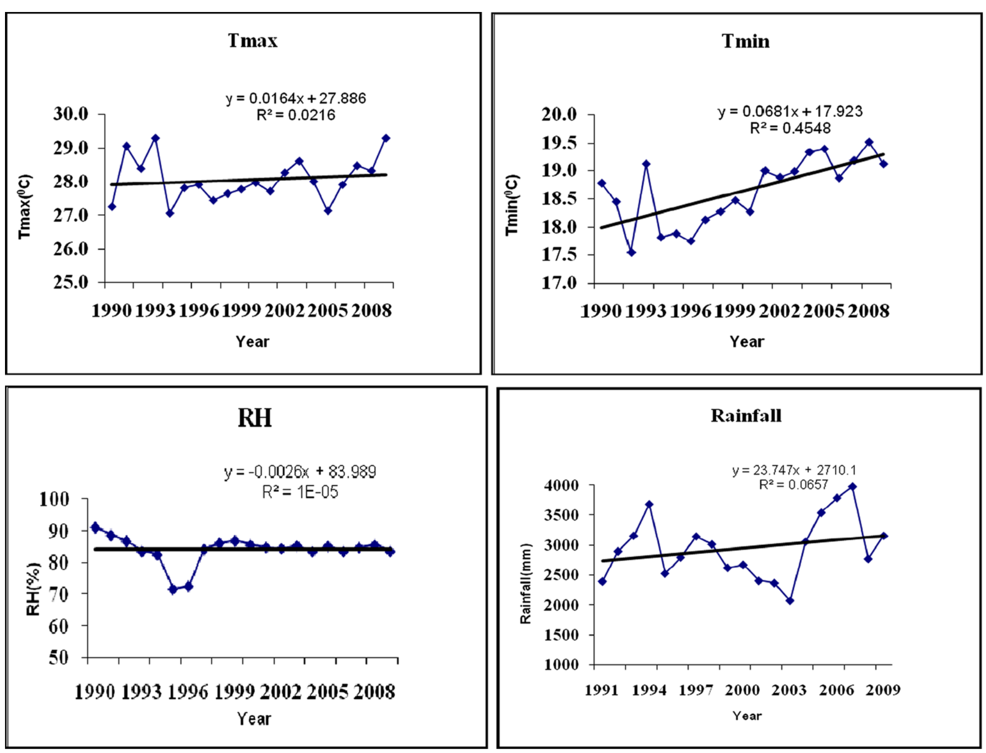

Fig. 1 Long-term trend of climate at Chundale

Coffee yield

Statistical analysis of long-term variability of coffee yield (1980–2009) revealed that yield of *C. arabica* and *C. canephora* coffee is found to be in increasing trend. The yield of *C. arabica* coffee was higher in 2001–2005 when compared to 1991–2000. This could be due to the planting of new species and adoption of scientific agro-techniques in the recent decade. However, the yield increase or decrease largely depends on the fluctuations in climate to a large extent and especially with blossom and backing showers of rainfall. The analysis of yield data showed that the yield of *C. canephora* coffee was higher than that of *C. arabica* coffee in Chundale, Wayanad (Fig. 2). Maximum yield of *C. canephora* coffee (2040 kg ha^{-1}) was recorded in 2003–2004. There was decline in yield subsequently in the following years. From the analysis, it was found that coffee berry production is decreasing in the Wayanad district, Kerala State, in recent years. This is similar to the trend observed in other parts of the state (Gopakumar 2011). The variability in monsoon rainfall along with the performance of pre-monsoon shower is likely to influence coffee production and its quality to a considerable extent. Maximum yield of *C. arabica* coffee (1745 kg ha^{-1}) was recorded in 1988–1989. Thereafter, declining trend of yield was noticed subsequently till 1997–1998.

Correlation with maximum temperature (Tmax) and minimum temperature (Tmin)

Correlation coefficients between yield of coffee and different climate parameters are shown in Tables 3 and 4. Correlation studies indicated that different climate parameters had significant influence on the yield of coffee. The yield of *C. arabica* coffee was positively correlated with maximum temperature in most of the months and whereas the yield of *C. canephora* coffee was positively correlated with maximum temperature during February. If climatic events such as overly high temperatures occur during sensitive periods of the life of the crop, for example during flowering or fruit setting, then yields will be adversely affected, particularly if accompanied by reduced rainfall (International Trade Centre 2010). In the present study, yield of *C. arabica* and *C. canephora* coffee, did not show significant correlation with minimum temperature in all the months of study. This is in contrast with the findings of Partelli et al. 2014, and they stated that when the minimum air temperatures are below 17.2 °C, the growth rate of *C. canephora* branches was sharply reduced for most of the genotypes studied. However, in our study, the values of minimum temperature never crossed the lower or upper limit mentioned in the suitability of climatic requirement during the entire period and that may be the possible reason for the non-significance (Table 1).

The yield of *C. arabica* coffee was positively correlated with maximum temperature during December, January, and February with highest correlation (0.7) during January and February. The yield of *C. canephora* coffee was positively correlated with maximum temperature during February (0.4). Coffee yield appears to be poor when the maximum temperatures go beyond 26.9 °C (Gopakumar 2011). The optimum mean annual temperature range for *C. arabica* coffee is 18–21 °C (Alègre 1959). Above 23 °C, development and ripening of fruits are accelerated, often leading to loss of quality. Relatively high temperature during blossoming, especially if associated with a prolonged dry season, may cause abortion of

Fig. 2 Yield variability in coffee at Chundale

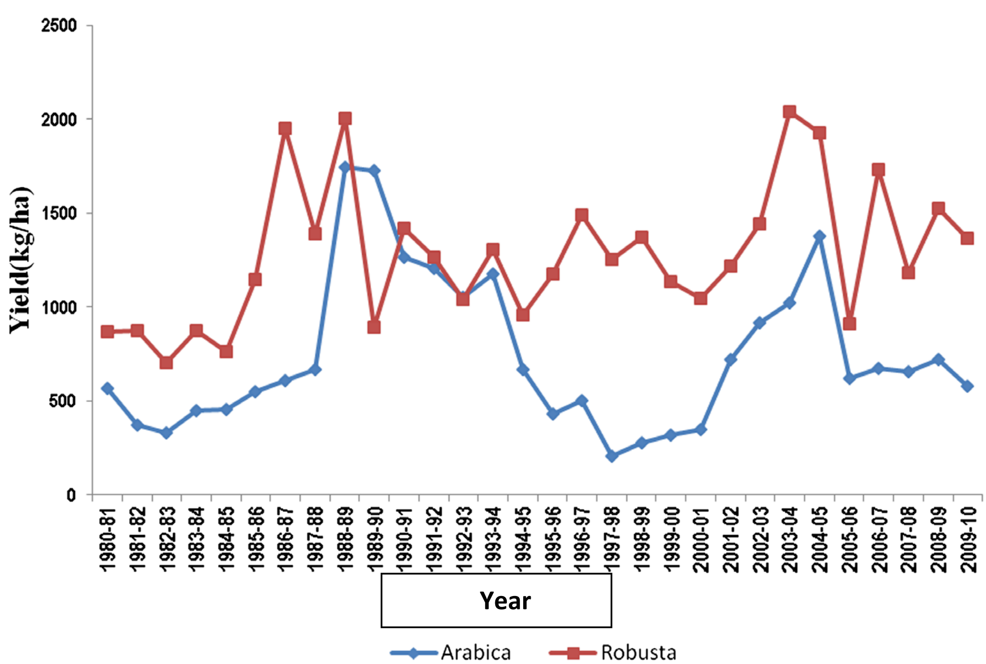

Table 3 Correlation coefficient (C.C.) between weather parameters and yield of *C. arabica* coffee at Chundale

Month	Weather parameters			
	Tmax	Tmin	RH	Rainfall
January	0.7[b]	−0.1	−0.1	−0.3
February	0.7[b]	−0.1	0.2	0.3
March	0.3	0.0	0.2	0.1
April	−0.2	−0.2	0.3	0.2
May	−0.4[a]	−0.2	0.4[a]	0.1
June	−0.2	−0.1	0.4[a]	−0.1
July	−0.3	0.0	0.4[a]	−0.2
August	−0.3	0.0	0.3	−0.2
September	0.0	−0.2	0.1	−0.2
October	0.1	−0.2	0.3	−0.1
November	0.0	−0.1	0.2	−0.3
December	0.5[a]	−0.2	−0.1	−0.4[a]

[a] CCs significant at 5 % level

[b] CCs significant at 1 % level

flowers (Camargo 1985). In regions with a mean annual temperature below 17–18 °C, the growth is largely depressed. In all the months of study, minimum temperature showed negative correlation with yield in respect to both *C. arabica* and *C. canephora* coffee.

In our study, difference is also observed between *C. canephora* and *C. arabica* in terms of correlation with the climatic parameters and yield. The possible reasons for both are discussed here under. Higher temperatures can be harmful, especially under low atmospheric humidity values (Coste 1992). By opposition, *C. canephora* plants are usually much less adaptable to cold than their *C. arabica* counterparts (DaMatta and Ramalho 2006; Partelli et al. 2009, 2011; Batista-Santos et al. 2011). When exposed to temperatures below 17 °C, branch growth is quite affected (Libardi et al. 1998; Partelli et al. 2010; Marré 2012), although some response variability can exist among cultivars, which might help selection for cultivation in different areas.

Table 4 Correlation coefficient (C.C.) between weather parameters and yield of *C. canephora* (*Robusta*) coffee at Chundale

Month	Weather parameters			
	Tmax	Tmin	RH	Rainfall
January	0.1	−0.1	−0.3	−0.1
February	0.4[a]	−0.2	−0.4[a]	0.5[a]
March	0.0	−0.2	−0.3	0.3
April	−0.3	−0.3	−0.2	0.0
May	−0.3	−0.3	−0.1	0.2
June	0.2	−0.1	0.0	−0.3
July	−0.1	−0.2	0.2	−0.4[a]
August	0.2	−0.2	0.2	−0.4[a]
September	0.0	−0.2	−0.1	−0.2
October	0.2	−0.2	0.1	0.0
November	0.1	−0.1	−0.2	−0.1
December	0.0	−0.3	0.0	0.0

[a] CCs significant at 5 % level

Moreover, the growth of leaves and orthotropic and plagiotropic branches follows the curves of minimum, average, and maximum temperatures (Amaral et al. 2006). In coffee, low temperatures (below the range of 13–17 °C) and pronounced water deficit (−3 MPa) affect various components of the photosynthetic process, as it reduces the stomatal conductance, net photosynthesis, photochemical efficiency of photosystem II, thylakoid electron transport, enzyme activity, and carbon metabolism as a whole. Low temperatures also affect the composition and structure of photosynthetic pigment complexes and of the lipid matrix of cell membranes, particularly in the chloroplast, although to different extent among genotype and species (Ramalho et al. 2003; Praxedes et al. 2006; Partelli et al. 2009, 2011; Batista-Santos et al. 2011). Such changes may reflect impairments or damages, and resulting in yield loss, whereas few genotypes may have the physiological mechanism to overcome it. Such acclimation ability on coffee genotypes seems to greatly rely on the control of antioxidative conditions, frequently linked to a lower photochemical use of energy through photosynthesis, as observed to happen under low temperatures (Ramalho et al. 2003, 2014; Fortunato et al. 2010), water deficit (Ramalho et al. 1998), and high irradiance and N-deficiency (Ramalho et al. 1998) stresses. Therefore, these changes would configure distinct morphological and physiological acclimation traits in *Coffea* spp. When cultivated at low temperatures (below 17 °C), *C. canephora* presents marked decreases in growth (Libardi et al. 1998; Partelli et al. 2010) and photosynthesis (Ramalho et al. 2003, 2014; Batista-Santos et al. 2011), with negative impact on yield. The climate parameters for the zoning of *C. canephora* species are based on the region of origin. Based on the previous study mentioned by various authors mentioned above, the current study clearly establishes the difference between two species on the climatic requirement for achieving better productivity. Thus, understanding the seasonal characteristics of the vegetative growth of both the varieties are required for developing proper management strategies to improve the productivity.

Coffee crops are often subjected to high temperatures in the summer, sometimes exceeding 38 °C during the critical grain-filling stage (Partelli et al. 2010, 2014). These conditions, combined with the occurrence of strong winds and high evapotranspiration rates, cause environmental stress for the crop, requiring different techniques to mitigate these problems. Along with the improvement in water conditions, the obtained benefits result in an increase in productivity, a reduction in yield costs, and in a valuable addition to the coffee crops in some marginal regions (Lee and Lee 2007). Therefore, the microclimate provided by trees in an agrosystem and its impact on coffee trees is important for this crop's management and viability.

Correlation with mean relative humidity (RH)

Correlation analysis between mean RH and yield of coffee indicated that mean relative humidity that prevailed during May, June, and July months did correlate positively with yield of *C. arabica* coffee with correlation coefficient of 0.4. There was no correlation between mean RH during the remaining months and yield of *C. arabica* coffee. However, a negative correlation (0.4) was registered between RH that prevailed during February month and yield of *C. canephora* coffee. There was no correlation between mean RH during the remaining months and yield of *C. canephora* coffee. Air humidity has a significant impact on the vegetative growth of the coffee tree. *C. canephora* successfully grows under high air humidity, while in contrast, *C. arabica* coffee requires a less humid atmosphere (Haarer 1958; Coste 1992). This is the possible reason for occurrence of such correlation results in the current study.

Correlation with rainfall (RF)

Rainfall in December showed negative correlation (0.4) with yield of *C. arabica* coffee. However, rainfall in remaining months do not have correlation with yield of *C. arabica* coffee yield. Rainfall in February (blossom showers) was positively correlated (0.5) with yield of *C. canephora* coffee, and rainfalls during July and August months were negatively correlated with yield of *C. canephora* coffee (0.4). The optimum annual rainfall requirement for *C. arabica* coffee is ranged from 1200 to 1800 mm (Alègre 1959). A similar range seems to be required for *C. canephora*, although it adapts better than *C. arabica* for intensive rainfall exceeding 2000 mm (Coste 1992), even though the Indian requirement given in Table 1 seems to be different. For both species, a short dry spell, lasting 2–4 months, corresponding to the quiescent growth phase, is important to stimulate flowering (Haarer 1958). Abundant rainfall throughout the year is often responsible for scattered harvest and low yields. Lack of a dry period can also limit coffee cultivation in lowland tropical regions (Maestri and Barros 1977). Generally between February 15th and March 15th flower buds will develop and ready for blooming in *C. canephora* coffee. Ideal time for receipt of blossom showers for coffee is mid-February to mid-March. Delay in blossom showers beyond March would affect the fruit set. A blossom rainfall of about 20–40 mm received either in 1 day or in 2–3 consecutive days during ideal time (February–March) is adequate for inducing normal blossom in *C. canephora* coffee. In *C. canephora*, if blossom shower is not received in time or in deficient quantity, then flower buds turn pinkish leading to a condition called "pinking" and fall. *C. canephora* is a very sensitive plant and easily responds to rain. It requires timely blossom and backing shower. If, *C. canephora* coffee plants do not receive blossom shower by March 15th, there will be a considerable loss of crop every week. Backing showers should be received within 1 month after the receipt of blossom showers. Seventy to seventy-five millimeters of backing rains is desirable for normal retention of newly set fruits. Any delay or absence of backing showers also would result in drying up of newly set fruits and thereby affects the final yield. In the present study also, both the species showed very poor yield when there were no blossom showers either in February or March, which might have resulted in poor flowering (Figs. 3 and 4).

In the present study, there was negative correlation of rainfall during July and August with *C. canephora* coffee yield and this was due to rainfall interception loss. Rainfall

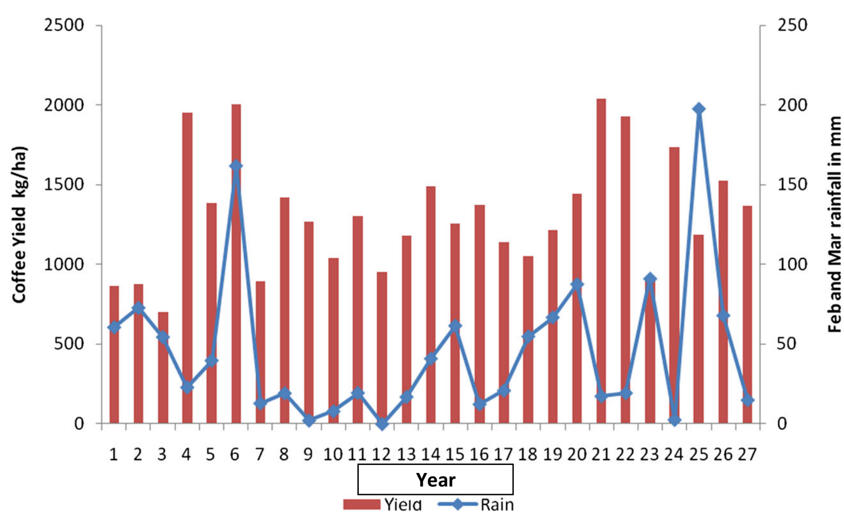

Fig. 3 Effect of blossom showers (Feb. and Mar. rainfall) on *C. canephora* coffee productivity

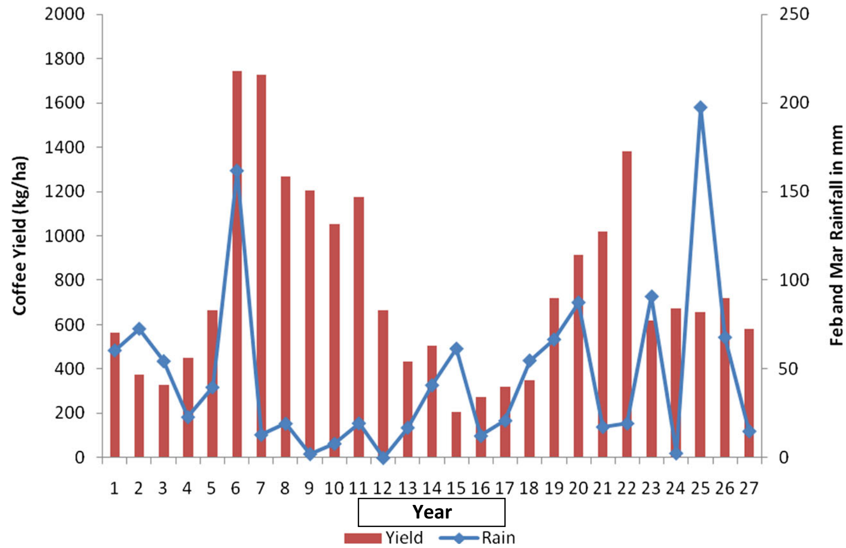

Fig. 4 Effect of blossom showers (Feb. and Mar. rainfall) on *C. arabica* coffee productivity

interception loss is defined as the rain water that is retained on the vegetation canopies lost to the atmosphere as water vapor. Rainfall interception loss from plants or trees can reduce a net rainfall as source of water yield. The amount of rainfall interception loss depends on kinds of plants and hydro-meteorological characteristics. Negative correlation ($r = 0.98$) between rainfall interception loss and yield of coffee was reported in Indonesia (Yulianur et al. 2012).

Statistical model

The values of the correlation coefficients for different climate parameters along with their significance at different levels are given in Table 3. The highest correlation coefficient was found between the yield of *C. arabica* coffee and maximum temperature during January and RH during July. Yield of *C. canephora* coffee had highest correlation with maximum temperature, RH, and rainfall during February in Chundale. The multiple regression equation which describes the average relationship between the yield of *C. arabica* coffee and significant climate parameters was derived and expressed here under:

$$Y = -7400.8 + 141.3\ X_{11} + 43.8\ X_{37}\ \left(r = 0.759, R^2 = 0.577\right)$$

Where Y = yield of *C. arabica* coffee, X_{11} = maximum temperature for January, and X_{37} = RH for July. The multiple correlation coefficients were significant.

Similarly, the multiple regression equation which describes the average relationship between the yield of *C. canephora* coffee and significant climate parameters was derived and expressed as below:

$$Y = -283.1 + 108\ X_{12} - 22.7\ X_{32} + 12.6\ X_{42}\left(r = 0.768, R^2 = 0.590\right)$$

Where Y = yield of *C. canephora* coffee, X_{12} = maximum temperature for February, X_{32} = RH for February, and

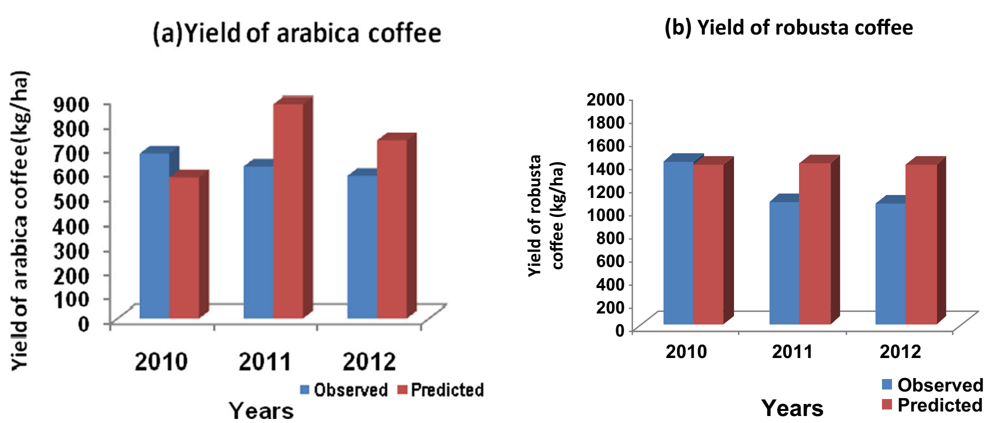

Fig. 5 Observed and predicted yield of *C. arabica* and *C. canephora* (*Robusta*) coffee

X_{42} = Rainfall for February. The multiple correlation coefficients were significant.

The multiple regression models developed for predicting the yield of *C. arabica* and *C. canephora* coffee at Chundale were validated using climate parameters for 2010, 2011, and 2012. Observed and predicted values of yield of coffee are presented in Fig. 5. Validated results showed that less than 10 % deviation during 2010 in both *C. arabica* and *C. canephora* coffee. During 2011 and 2012, deviation is more than 10 % due to high predicted yield of *C. arabica* coffee. This is due to high maximum temperature during January than normal maximum temperature (28.8 °C) which has highest correlation with *C. arabica* coffee yield. Similarly, high maximum temperature during February compared to normal maximum temperature (29.8 °C) resulted in high predicted yield of *C. canephora* coffee. These climate parameters forecasting model, will help the farmers in effectively plan their management activities (Surendran et al. 2014, 2016a). Farmers should be trained in such a way to know about the whole system of their farm, how climate change is influencing the coffee productivity, and also awareness should be created about the activities which can mitigate the impact of climatic parameters and also training on efficient management techniques to mitigate them (Surendran and Murugappan 2010; Surendran et al. 2016b).

However, to get more robust forecasting models, long-term climate and production data are required. To strengthen the confidence and relevance of our findings, it would be very valuable if similar studies were conducted in other coffee-growing areas. This study provides the first evidence that climatic parameters have direct influence on coffee productivity and it is very vital at the scenario of climate change. These suggest that, the forecasting model may be utilized for different climate scenarios and climate change adaptation strategies can be suggested. Such studies, if properly used, can create awareness in public and private-sectors to invest and that will better sustain this important industry and the livelihoods of millions of smallholder farmers who depend on it.

Conclusions

(i) Long-term analysis of yield data of coffee revealed that the yield of *C. canephora* coffee was higher than *C. arabica* coffee in Wayanad region of Kerala.

(ii) Yield of *C. arabica* coffee was positively correlated with maximum temperature during January and RH during July and yield of *C. canephora* coffee was positively correlated with maximum temperature during February and negatively correlated with RH during February. These parameters were considered when developing the forecasting model.

(iii) Statistical forecasting model between climate and yield of *C. arabica* and *C. canephora* coffee was developed and the model was validated with the available data. Using the model, it is possible to forecast the yield of *C. arabica* and *C. canephora* coffee for future climate change scenarios, which can be used to plan the climate change adaptation strategies.

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