# Climate Change Scenarios, Their Impacts And Implications On Indian Cardamom-Coffee Hot Spots, One of The Two In The World

**Murugan Muthusamy** ( muthupeyan@gmail.com )
Cardamom Research Station, Kerala Agricultural University, Pampadumpara,India
https://orcid.org/0000-0001-9449-1039

**M Alagupalamuthirsolai**
IISR: Indian Institute of Spices Research

**K Ashokkumar**
Cardamom Research Station, Kerala Agricultural University, Pampadumpara,India

**A Anandhi**
FAMU: Florida Agricultural and Mechanical University

**R Ravi**
Indian Institute of Science

**R Rajangam**
Tamil Nadu Agricultural University

**M.K Dhanya**
Cardamom Research Station, Kerala Agricultural University, Pampadumpara,India

**K.S Krishnamurthy**
Indian Institute of Spices Research

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# Abstract

In this study, we investigated climatic parameters as well as predicted future change in precipitation and atmospheric temperature levels based on RCP4.5/8.5 scenarios in all cardamom-coffee hot spots of southern India. Our results showed that larger precipitation levels and pattern occurred in Cardamom hills (Kerala) followed by lower Puleny hills in Tamil Nadu. The least variation in precipitation levels has noticed for temperate upper Puleny hills and Kodagu hills in Karnataka. RCP4.5/8.5 scenario analysis showed greater variability in precipitation up to 180% increase and 90% decrease for all hot sports. The scenario analysis also predicted extreme variation in temperature levels ranging from 0.5–8.5ºC increase for the entire study region. A significant change in the coffee yield and quality has been recorded over the last 30 years. Increased yield trends in coffee were noticed for Cardamom hills (CH) and Kodagu hills, but significantly lower coffee production was observed for lower Pulney hills. The mixed response of yield variability in coffee has been primarily attributed to the ongoing changing climatic factors. Ecophysiological studies of coffee, cardamom and black pepper have proved that coffee would adapt well to a future challenging climatic condition, closely followed by cardamom and black pepper. Since all the coffee-cardamom hot spots in southern India undergoes considerable change in precipitation levels and pattern, necessary precautions, including water and irrigation management strategies, must be given utmost priority to increase the crop yield sustainability of these delicate cardamom-coffee hot spots in India.


# Introduction

Indian cardamom-coffee hot spots are one of the two unique and important tropical mountain ecosystems globally for a growing variety of crops, e.g., spices, fruits and vegetables. The other is located in Guatemala, where maize and tapioca are also cultivated along with cardamom and coffee. Generally, farmers' livelihoods in tropical mountain agriculture in southern India depend largely on growing high-value spice crops and seasonal vegetables and fruit crops. These hot spots in India have peculiar environments mainly due to altitudinal variations and specific geographical locations concerning the Indian monsoon and its seasonal winds. Agroecosystems in tropical mountains are highly sensitive and vulnerable to climatic change, thereby reduction in crop yields. Agriculture across the world is under stress leading to diminishing returns and productivity. The relative rates of yield increase for all of the major cereal crops as well as plantation crops are already declining (Ainsworth and Ort, 2010; Murugan et al. 2012).

The world's coffee-cardamom sector provides employment and livelihood for over 60 million people in the tropics. It is considered the second largest employment sector in the world after the oil industry. Correspondingly, India is the sixth and second-largest coffee and cardamom producing country globally, accounting for over 4 and 40% of the world's production, respectively. More than 92% of the Indian coffee and the entire cardamom production come from Karnataka, Kerala and Tamil Nadu. Area, production and productivity of coffee are maximum for Karnataka, followed by Kerala and Tamil Nadu. Kerala is the leading producer of small cardamom in the country, chased by Karnataka and Tamil Nadu. The major share of coffee and cardamom production in India originates from small to medium farms, which are more vulnerable to climatic change and variability. Both cardamom and coffee prefer elevation induced natural forest ecosystem for sustainable production. Cardamom being more closely related to rain forest environment the sufficient surface soil moisture is indispensable. Coffee, which requires cooler subtropical climatic conditions, is relatively less sensitive to drought under optimum natural forest shade. Hence, these crops are predominantly cultivated both in the high ranges and the high uplands of the Western Ghats (WG) in southern India. Except the Upper Pulney hills (UPH), where many temperate fruits and vegetable crops are also mainly farmed, the other hot spots are cultivated with only high-value spices and plantation crops. Most coffee farms in these states are concentrated in the WG high uplands. The rich history of coffee cultivation in Pulney hills is very old, whereas it is relatively new and peculiar to Cardamom hills (CH). Both Arabica and Robusta spoils approximately 50% share in acreage.

Upper Pulney hills (UPH) are the largest highland massif in southern India (Raith et al. 1997). Geographically, the unique Pulney hills form a part of the widest portion in the entire WG, which are considered one of the Global Biodiversity hot spots. Fyson et al. (1915) first published authentic and science-based information about the biotic richness flowering plants of the temperate Kodaikanal hills. One of the Global Atmospheric Watch (GAW) stations was positioned in Kodaikanal hills considering the geographical superiority over other hills in India5. South of the Himalayas, the longest high-plateau (7700 feet msl) is supposed to have more diversified agricultural/sylvicultural/sylvipastoral and socio-economic significance and activities than the other hot-spots.

According to (Smith, 1895), the overall climate of the UPH used to be a splendid one, combining many of the advantages of tropical and temperate regions; for instance, the mean relative humidity varied from 47% in March to 83% in August and the mean for the year being 72%. The actual annual total rainfall around 1895 was 47.5 inches at the observatory site. Still, slightly increased rainfall (20% more) was reported for a station little away from the observatory at higher elevation cliffs (61 inches). The rainfall was spread over all months, being highest for August (21 days) and lowest for March (3 days). There were 2065 hours of sunshine annually. The impact of orography characterizes the rainfall pattern over these high ridges and valleys. Hence the rainfall activity spread across all the seasons rather than a single season. The western high ridge plateau of the hills experiences a temperate environment. At the same time, the lesser elevated eastern (1000–2000 msl) slopes enjoy the tropical and subtropical climate, which mostly comes under Lower Pulney hills (LPH). Overall, the average annual total rainfall, 41%, 35%, and 24%, correspondingly contributed by northeast and southwest monsoon and summer months. Thus, the entire region has a magnificent climate with many advantages of tropical and temperate regions. That is why a variety of crops ranging from temperate fruits (Pear and Plum) to vegetables (Cole crops, Beans) further to tubers (Potato and Carrot) and plantation crops (coffee and pepper) are successfully cultivated in these hills throughout the year. And, as such, any change taking place in the patterns of climate parameters, for instance, temperature and rainfall, attracts value amongst researchers and agriculturalists concerned.

The main factors that control the growth and development of diseases in plants are temperature and precipitation (water) by affecting factors such as the plant pathogen's survival, vigor, rate of multiplication, sporulation, direction, distance of dispersal of inoculums, and rate of spore germination and penetration (Yáñez-López et al. 2014). Hence, studies assessing the impact of climate change in agriculture have mainly focused on the effects of temperatures and precipitation while considering agricultural production and the impact of insects, pests and diseases. Increases in the growing season change the evapotranspiration and have implications on the water demand in managed ecosystems (Anandhi et al. 2013a & 2013b). Specific stages of growth (e.g., flowering, pollination and grain filling) are susceptible to weather conditions and critical for final yield (Lavalle et al. 2009). As global temperature rises, crops will increasingly begin to experience failure in traditional production regions, especially if climate variability increases and precipitation lessens or becomes more variable. Atmospheric temperature and rainfall variability play a significant role in crop growth and yield.

Climate change in managed ecosystems is likely to alter the availability and distribution of freshwater (e.g., floods, droughts) while simultaneously increasing the demand for water from rivers and impacting groundwater availability (Allan et al., 2013). In addition, rising temperatures have shown to impact the phenology of plants and insect (Anandhi et al., 2016) [shifts in the timing of plant and insect activity]. Plant response to climate change is realized through a complex set of interactions among CO2 concentration, temperature, solar radiation, and precipitation. Temperature, precipitation, sunlight, and air humidity are also primary climate factors that control the growth and development of insects, pests, and diseases in crops (Esbjerg and Sigsgaard, 2014). However, observed data on climate variables such as solar radiation and humidity for these hot spots are sparse compared with rainfall and temperature (Anandhi et al. 2012 & 2016).

The production physiology of coffee is unique among crops. The crop prefers a sub-tropical (cool dry) condition for growth with optimum temperature being18-26˚C. However, it requires another particular condition of inductive stress followed by a medium to heavy rainfall that triggers the entire flowering process. The tricky physiology coffee of flowering has been probed, and on which convincing results are available. The term blossom showers give a meaningful representation of how much summer showers means to productivity in coffee. This could also be why nature has placed the original habitat of coffee in an area with tropical showers blend with cool winters.

The flowering aspects of coffee have been extensively studied and documented (Huxley, 1970; Browning, 1975) and extensively reviewed by Cannell (1985). This is points to the summer stress and summer showers as pre determinants of flowering requirement. The crux of these works revolves around the production of hydrolytic enzymes brought about by a favorable balance of hormones, namely GA/Auxins that initiates flowering. There is also compelling evidence to suggest a reduction in abscisic acid levels, which releases the dormancy of flower buds with the receipt of the first rains (Barros et al., 1978; Rena et al., 1994). Thus, the three critical requirements of inductive stress, the blossom showers and backing rains, are the most critical aspects that govern flowering and productivity in coffee. The timely receipt of showers and the intensity to break down the dormancy of flower buds are the points of immediate concern in the WG. Limited water availability can cause an increase in crop failure (defined as the complete loss of crops on a farm)7. The LPH where coffee is grown is now seen to have a prolonged drought situation in summer, posing a challenge to the very existence of the crop there. The case in CH is that the summer shower has become erratic and subjected to cause increased stress often. Wynad district in Kerala, where coffee is mainly grown as a sole crop, climate change has been felt, and coffee production and productivity have been rendered vulnerable. This has led to an agrarian crisis, with farmers resorting to suicide as it is the mainstay of livelihood. The neighboring Coorg district in Karnataka has not yet frequently witnessed climate change compared to Kerala and Tamil Nadu, mostly because large-scale deforestation is yet to occur.

The cardamom sector is much more organized with very high inputs, but this *Zingiberaceous* crop is very sensitive to climatic vagaries. This is also another crop that requires little stress during early February and with the onset of monsoon profusely tillers under rainfed condition. It is from the base of such healthy tillers or stout tillers that the panicle arises. Longer wet spells drive the production of panicles from the previous season tillers. Another important aspect is that the lengthening of the panicles bearing the flowers and the consequent fruit set is again dependent on the length of wet spells or otherwise has to be managed or supplemented by irrigation.

Thus, we have two typical clear cut crop stages with distinct requirements that is dependent on environmental conditions

1. Inductive summer stress followed by summer showers for floral induction of coffee followed by backing rains for berry set and development and
2. Stress followed by rains for tillering (emergence of new shoots) and panicle initiation from the base of stout tillers and panicle growth and flowering and fruit set with persistent rains in cardamom.

Any limitation to this sequence or change in the intensity and calendar of events like prolonged or frequent drought, non-receipt of timely rainfall and delayed and non-optimal receipt of continued rainfall could offset the entire production cycle, leading to reduced crop yields. Thus, the critical environmental conditions have paved the way for different phenophasic development in both crops.

Relative rates of yield increase for all of the major cereal crops are already declining1. The assumptions such as yield improvements from the latter half of the 20th century will continue may not be sound because they are based on historical temperature-crop yield relationships, potential ceilings to crop yields, and limitations to expansion of agricultural lands1. Under conditions of climate change and increased human activity, the stresses and vulnerabilities associated with a water supply and water demand will increase significantly across the world (Allan et al. 2003).

Agriculture is vulnerable to climate change and variability through direct (i.e., abiotic) effects on crop development and yield (e.g., changes in temperature or precipitation) as well as through indirect effects arising from changes in the severity of pest, insect, and disease pressures; availability of pollination services; and performance of other ecosystem services that affect agricultural productivity (Walthall, 2012; Anandhi and Blocksome, 2017). However, continuous long-term data on climate variables such as solar radiation and humidity are sparse compared with rainfall and temperature (Anandhi et al. 2012 and 2016). Present and future climatic change may present unprecedented challenges to coffee-cardamom cultivations by influencing crop distribution and production and increasing the economic and environmental risks associated with the production systems. Therefore, critical analysis and insights into the observed climatic variability and yield of crops could be useful for scientific and farming communities to better manage the delicate Indian cardamom- coffee hot spots.

# Materials And Methods

Long term climate data from four representative climate stations located in three south Indian states and productivity data of select crops were subjected for statistical analyses. Future rainfall variability and patterns for all three montane hot spots were also studied. The future climate of small-scale tropical mountains is uncertain and unknown. Global Climate Models (GCMs) are among the most advanced tools that simulate climatic conditions hundreds of years into the future. The scenarios are often used in investigating the potential consequences of anthropogenic climate change and natural climate variability. A scenario is a coherent, internally consistent and plausible description of a possible future state of the world. Farmer's survey was also conducted to understand the grower's perception of climate change implications.

### Data Used

The fifth phase of the Climate Model Intercomparison Project (CMIP5), a freely available state-of-the-art multi-model dataset (multiple GCMs and RCPs), was designed to advance our knowledge of climate variability and climate change. Monthly simulations of precipitation and temperature from 35 GCMs that participated in the CMIP5 were used in this study. Results from historical (1986-2005) and future (2006-2099 and 2006-2099, RCP4.5 and RCP8.5) experiments were investigated. Further information on the experiments and models is available on the CMIP5 website (http://cmippcmdi.llnl.gov/cmip5/). The data were extracted and interpolated to a common 1.5° grid square using bilinear interpolation.

Simulations from 35 GCMs participating in CMIP5 for two future emission scenarios (RCP4.5 and RCP8.5) provide a wide range of potential climate change outcomes. Moreover, the results could be later used to access both mitigation and adaptation alternatives to reduce vulnerabilities in managed ecosystems (agriculture and urban systems) and water resources. This paper tried to explain and explore how current climate change and variability had impacted the yields of select crops grown in these delicate mountain ecosystems by statistical analysis and comparison. Regression models were used to explain the crop yields' variability using growing season climate data.

### Developing incremental scenario

Scenarios can be created using simple downscaling methods such as change factor methodology (Anandhi et al. 2011). The scenarios thus obtained were also referred to as synthetic scenarios (Anandhi et al. 2018).

Step1: Grids were identified: 11 grids cover the study region (highlighted in yellow in Fig. below). Each grid has 70 monthly time series for (35 GCMs/runs for rcp 4.5/rcp 8.5). Therefore the 770-time series (70 monthly time series each for 11 grids) were analyzed.

Step2: All the 770 time-series were plotted for each variable (Fig. 5a & 6a).

Step3: 24 month moving averages from each of the 770 time-series were plotted for each variable (Fig. 5b & 6b).

Step4: Change using equation 1 for Precipitation and equation 2 for temperature was estimated and plotted in (Fig. 5c & 6c).

$$Change_{i,c} = \frac{(GCMf_{i,c} - GCMh_c)}{GCMh_c} \times 100 \qquad (1)$$

$$Change_{i,c} = (GCMf_{i,c} - GCMh_c) \qquad (2)$$

Step5: All 11 grids' time series for RCP 4.5 scenarios were combined for a variable and then estimated the percentiles 5, 10, 15, 25, 50, 75, 90 and 95 percentiles and plotted them (Fig. 5d & 6d). Did the same for RCP 8.5 (Fig. 5e & 6e).

Step6: Boundary of the scenario funnels was developed. Estimated the 24-month moving average of the percentiles 5, 10, 15, 25, 50, 75, 90 and 95 percentiles and plotted them (Fig. 5f & 6f). The same was repeated for RCP 8.5 (Fig. 5g & 6g). Thus, each RCP had 3 funnels with 6 boundaries (blue, red, yellow).

Step7: The funnel boundaries were plotted for the 2 RCP in a single plot (Fig. 5h & 6h) and the changes were observed.

## Ecological physiology of shade grown cardamom, coffee and black pepper

Experiments were conducted during a warm-weather condition in March 2019 at the research farm, ICAR-Indian Institute of Spices Research, Regional Station, Madikeri. The study was carried out on yielding plants of coffee, cardamom and black pepper under natural condition (natural forest). All the observations were carried out in 10 days to avoid seasonal changes. Newly expanded mature leaves, i.e., the third leaf in the experimental plants were studied.

## Leaf gas exchange

Gas exchange measurements were obtained using a portable photosynthetic system (LCpro-SD Advanced Photosynthesis Measurement System, England). Net photosynthetic rate (Anet, μmol CO2 m-2 s-1), stomatal conductance (gs, mol H2O m-2 s-1) and transpiration (E, mmol m-2 s-1), instantaneous water-use efficiency (WUEi) was calculated as the ratio of net assimilation (Anet) to transpiration (E). Diurnal variation of gas exchange parameters was collected in the field-grown plants during the summer season at 2-h intervals from 7:00 to 17:00 h over 2 consecutive days per population. The measurements were recorded when both Anet and gs were stable.

In addition to the ecophysiological measurements, micro-environmental parameters at the natural stands of the select sample populations were recorded. Light availability was measured as photosynthetic photon flux density (PPFD) (μmol m-2 s-1), reflecting ambient conditions at the specific measurement date. The difference in the water vapour pressure (VPD; mbar) was also computed. The leaf-Leaf temperature ($^{o}$C) and Ci- intercellular $CO_2$ concentration (ppm) were also measured.

### Chlorophyll fluorescence

*In vivo* chlorophyll fluorescence was measured using a chlorophyll fluorometer (Os-30p) in 10-15 minutes dark-adapted leaves on the same plants as those used for leaf gas exchange measurements. The maximum PS II quantum yield (Fv/Fm = (Fm – Fo)/Fm) was determined in dark-adapted leaves at 2h intervals from 7:00-17:00h local time according to Strasser et al. (1995). Gas exchange and chlorophyll fluorescence were analyzed on a typical sunny day. All measurements were performed on the fully expanded leaves with 30 observations.

## Results And Discussion

# Observed climatic variability in coffee-cardamom hot spots

All hot spots have registered climatic variability, but the levels of variability varied among the hotspots depending on the specific geographic location (Fig. 1–4). Rainfall variability was maximum for CH followed by LPH. Temperate UPH and Kodagu hills (KH) have experienced little variation in rainfall. Interestingly UPH has recorded increased rainfall amounts over the study period. Extreme variability in air temperature and rainfall was notified for LPH and UPH. Temperature showed a downward trend in upper Pulney hills. KH showed increased rainfall during the first two seasons, whereas the rainfall during October and December showed decreasing trend. Increasing trends of rainfall were registered at cardamom hills for the first two seasons. The third season rainfall recorded a declining tendency.

The observed variability in precipitation levels on seasonal and monthly scales was the greatest for LPH and UPH (Tamil Nadu), followed by CH (Kerala) and KH (Karnataka). Variation in the amounts and pattern of seasonal rainfall has not changed much during the period (1978–2014) at higher altitude UPH (Kodaikkanal station). Rainfall during the summer months (Jan-May) had contributed 24.08% (372.06 mm) while the first (June – Sep) and second monsoon months (Oct-Sep) had respectively given 34.64(541.3 mm) and 41.28% (649.23 mm). Annual total effective sunshine hours (SSH) declined over the study period, and its range was 1775.7-2005.3 hours. Minimum monthly SSH ranged from 14.8 to 70.3 hours. July recorded the least, while February was the sunniest month. The distribution of rainfall had not changed much in UPH, but other climatic factors had changed a lot from the earlier observations reported by Smith (1895)5. Increased rainfall amounts have been recorded in UPH for the study period on seasonal scales, besides a significant variability in atmospheric air temperature and relative humidity. Maximum and minimum temperatures across the seasons declined, except the summer months. A notable reduction in diurnal temperatures were registered for all seasons. Atmospheric relative humidity showed positive trends in all seasons in UPH. Similar findings and observations were also made in the previous analysis of Rangan et al. (2010).

The observed atmospheric air temperature (T min) in the regions consistently increased, causing significant challenges in the water management of these sensitive crops. The productivity of the crops was highly variable with hotspots (Figs. 7, 8 and 9). Coffee yields have decreased significantly over time in LPH, while a considerable increase was observed for the other two hotspots CH & KH. Even a forty per cent decrease in annual total rainfall did not affect the yields of coffee in CH during 2017-18 but reduced the cardamom yield to nearly 50%. Increasing atmospheric air temperatures coupled with high precipitation amounts could further stress groundwater reservoirs of the region, leading to withdrawal rates that become even more unsustainable for the mountainous regions. High precipitation variability (with a higher propensity for localized intense rainfall events) observed in the region can be a key factor for these ecosystems water management. In future, the results could be used to develop and plan both mitigation and adaptation alternatives to reduce vulnerabilities and increase yield sustainability of the hot spot.

# Future climate change based on RCP 4.5/8.5 (Precipitation and temperature)

Agriculture is vulnerable to climate change and variability through direct (i.e., abiotic) effects on crop development and yield (e.g., changes in temperature or precipitation) as well as through indirect effects arising from changes in the severity of pest, insect, and disease pressures; availability of pollination services; and performance of other ecosystem services that affect agricultural productivity Walthall, (2012). In tropical regions, heavy rainfall and strong winds are destructive to crops (Lansigan et al. 2000). Studies have shown that high rainfall events over parts of India are increasing (Ramesh and Goswami, 2014; Karmakar et al. 2015). This can impact agricultural production and urban water management. Heavy rainfall just before harvesting decreases yields in many regions of the world. Mean temperature, mean precipitation, and the number of days with precipitation were correlated to changes in insect phenology, date of the first appearance, changes in insect generation time, number of generations per season, and geographical location distribution (Esbjerg and Sigsgaard, 2014). Changing temperatures can change the crop development stage, which can change the crop water requirement in general and cause water stress to plant growth, which may impact yield. These can have important implications for water resource management in the region. Our results showed high variability in the future change in precipitation and temperature in all hot spots. A high variability in the future change in precipitation and temperature was noticed for the entire region. Variability in rainfall and its unique pattern (with a higher propensity for localized intense rainfall events) was observed for the region, which can be a key factor for these ecosystems, particularly crop water management of these sensitive, delicate mountain region.

Based on global scenarios, the Intergovernmental Panel on Climate Change (IPCC) predicted an increase in the mean global climate ranging 1.4–5.8˚C by the end of this century (IPCC, 2007) 29. Climate change is also projected to cause more frequent and intense El-Nino-Southern Oscillation (ENSO) events leading to widespread drought in some areas and extensive flooding. Consequently, such events will negatively impact the availability of water resources, food and agricultural security, human health and biodiversity (Wara et al. 2005). Presently, studies on the impact of nighttime (minimum) temperature on tropical crops have been significantly improved, particularly in southeast Asia and India (Nagarajan et al. 2010; Rao et al. 2014; Murugan et al. 2017). Indeed, the global scale minimum temperatures have increased twice as fast as the maximum temperature (Vose et al. 2005; de los Milagros Skansi et al. 2013). Recently, South African scientists have demonstrated a solid significant negative influence of nighttime minimum temperature on coffee productivity in *C. Arabica* (Craparo et al. 2015). Scenario analysis based on the Representative Concentration Pathway (RCP) (6.0) for Tanzanian high lands also predicted that there will be a drastic change in the future minimum temperature that will be very severe in the interior parts also where the major Arabica growing regions are located (Meinshausen et al. 2011).

Global average air temperature is predicted to increase by approximately 6.0°C by 2100. The CO2 concentration is expected to increase to 940 μmol/mol and the precipitation to increase by 20.4% from existing conditions under the RCP 8.5 CC scenario. The Representative Concentration Pathway (RCP 4.5/8.5) predicts moderate to extreme variation in the temperature range from 0.5 to 8˚C for the entire study location. Planters cultivate coffee under natural forest (shade-grown coffee) while it is purely sun-grown crop in eastern Africa. Under a modest climate change scenario (RCP 4.5), coffee can tolerate and yield reasonably because of the buffering and shading effect of natural forest. Approximately 8˚C has been predicted for the Indian coffee hot spots under RCP 8.5 climate change scenario. The hot spots will experience extreme temperature coupled with the tremendous change in the precipitation levels (180% increased and 90% decreased) will have severe implications and negative impacts on the growth, development and yield of coffee, cardamom and pepper plants. Under unusually low precipitation (90% decreases) scenario, the coffee plants can be affected severely by disruption of photosynthesis, flowering and fruit set, and other physiological abnormalities. Thereby both the yield and quality of coffee berries will be impacted negatively under future changing climate scenario. The surface and subsurface soils become extremely more complex due to extremely low rainfall, and the complete withering of young coffee plants can be anticipated depending on the slope gradient. High-intensity rainfall (180% increase) will cause the shedding of harvestable berries (matured coffee berry) besides flower dropping during the blossom period. Honeybee activity is highly disturbed by incessant rainfall, affecting pollination and reducing the cardamom yield up to 40% (the case of 2018). In pepper, pollination and berry development in the spikes are affected due to continuous rain. In some of the past years, the hot spots across the states have received even 30 inches of rainfall in a day during October-November that caused 50% crop loss in coffee. Scientific evidence and information on climate change impacts based on RCP scenarios for coffee are very scanty. Still, published information on similar RCP scenarios for crops like hot pepper showed extreme negative impacts on physiological disorders and morphological deformities of Chillies (Capsicum) (Lee et al. 2017).

# Variability in climatic factors and coffee yield in the hot-spots

India is the leading producer of coffee in Asia, where both Arabica and Robusta are grown under significant acreage. Spatio-temporal variability in coffee yields was exhibited among Indian cardamom and coffee hotspots. Year to year variation in coffee yield was observed among the regions depending on the precipitation pattern and temperature influenced by ENSO of the respective years. The localized phenomenon, particularly the altitude and slope gradients also associated with the variability in the coffee yields. Declining and increasing trends were observed correspondingly for Tamil Nadu and Kerala hot spots, while the productivity was more or less static for the Karnataka region (Fig. 7–9).

Insufficient rainfall during the flowering phase (Feb-Mar) and heavy intense rainfall during the maturity to ripening stage (Nov-Dec) caused yield losses in coffee. Such damage has been more pronounced in Arabica than Robusta. Precipitation pattern before and after the first monsoon plays a significant role in deciding the yield of coffee in all three hot spots. Most of the coffee plantations in LPH (Tamil Nadu) are located on lee side of the southwest monsoon; therefore, the region enjoys lesser annual rainfall. The minimum temperature levels were very high for the summer months (Jan-May), which, along with the poor distribution of summer months' rain, could have caused the decline in production. Recently, smallholding coffee farmers in southern India tend to abandon coffee fields because of unfavorable market price. Many growers follow cost-cutting practices, including inputs like fertilizers, chemicals and manures. As far as biotic stresses are concerned, white stem borer is a severe problem in Karnataka coffee-growing areas, but in other regions in Kerala and Tamil Nadu, the pest incidence is minimal. At present, Robusta coffee's productivity is increasing due to its tolerance to insect pests and diseases as well as environmental stress. Arabica coffee is experiencing stagnant productivity as well as lower market price.

The ongoing climate warming and precipitation pattern change in these hot spots are two important factors affecting both coffee and cardamom yields. In coffee, Arabica type is on the higher side of the risk than the Robusta. The early maturity of coffee has both positives and negatives. For example, a better market price can be anticipated for Arabica, but at the same time, heavy downpours of up to 30 inches of rainfall in a day can destroy the crop during the second monsoon months like October-November. Such intense rainfall during November in the Karnataka region is less expected, and therefore it is advantageous there. But in Kerala and Tamil Nadu, where the northeast monsoon is still active, during which time the matured crop can get destroyed, it is not benevolent for Kerala and Tamil Nadu planters. Early summer showers (February) in all regions lead to early crop, but atmospheric warming along with intense rainfall and strong surface winds destroy coffee and cardamom significantly. Extension of dry period by a month (March-April) leads to late crop, which coincides with heavy rainfall during winter monsoon (November-December) and damages the coffee crop severely in Kerala and Tamil Nadu regions. Overall, it is observed that the production of coffee is at increased risk in all coffee growing hotspots in southern India. Therefore, planters need to take extra care to cope with the unfavorable climatic condition and variability.

# Recommended adaption strategies and farmers perspectives

There has been a significant change in the forest tree species composition of cardamom-coffee hot spots over the last three decades. At least 50% of trees in the CH hot spot composed of only three species, namely *Vernonia arborea* (Karana), *Artocarpus heterophyllus* (Jack) and *Toonaciliata* (Cedar). The population of notified native forest trees is declining, and they are all very old and facing severe elimination. To maintain uniform and required shade level, the planters must increase tree density and diversity significantly. Except for Jack, the other two major species are highly vulnerable to wind damage. Maintaining good shade levels in coffee plantation in Kerala and Tamil Nadu delays early maturity; thereby, the berries ready to harvest will not suffer from a heavy downpour during the winter monsoon period.

Interestingly, the Karnataka regions escape from this problem since the monsoon rain never damage the matured coffee berries in November - December. Planters also use chemicals (Cobalt sulphate 375 g/ ha) to delay the maturity and ripening of coffee berries at least by 15–20 days so that the damage and loss of mature coffee beans due to heavy rain can be thwarted. Anticipating the extreme temperature and precipitation levels as given by the RCP climate change scenario, multiple canopy levels are recommended with various tree species, mainly species with broad leaves because needle-shaped leaves (*Grevellia robusta*) allow more sunlight to fall on coffee and cardamom canopy, which will have serious implication under future warming and precipitation levels. Our objective is to reduce air and crop canopy temperature levels for which tropical evergreen species are the most preferred ones. Planters in lower rainfall areas of Tamil Nadu and Kerala go for subsoil irrigation along with fertigation to safeguard the younger coffee plants from drought and water scarcity. Most planters and growers in the hot spots perceive and recognize drought and climate change as the most critical aspect affecting the productivity of long duration and perennial crops, followed by irrigation water availability and scarcity and insect pests and disease problems. Nearly 60% of farmers rank unfavorable market price as an important factor affecting agricultural sustainability, followed by problems with pesticides (39%) and water quality degradation (28%) in the hot spot areas. These are concerned as the present and future health externalities. Shade level and forest degradation (27%) as well as loss of topsoil and degradation (15%) rank as the penultimate and ultimate problems of the planters (Table 3).

**Table: 1. a)** Name of the metrological station and geographical location details of cardamom-coffee hot spots

| Cardamom-Coffee hot spots and crops grown | Latitude of the study area/site | Longitude of the study area/site | Altitude of the study area/site |
|---|---|---|---|
| Cardamom hills, (Kerala)<br>(Cardamom and Coffee)<br>(1978-2016 period) | 9 15 N-10 0 N | 76 45 E – 77 25 E | 1100 msl |
| Upper Pulney hills (Kodaikkanal, Tamil Nadu)<br>(Bean, Carrot, Cabbage, Pear, Plum and Potato)<br>(1978-2015 period) | 10 20 N | 77 50 E | 2300 msl |
| Lower Pulney hills (Manalur, Tamil Nadu)<br>(Coffee and Cardamom)<br>(1990-2015 period) | 10 00 N | 77 00E | 1098 msl |
| Kodagu hills, (Madikare, Karnataka) | 13 80 N | 75 38 E | 1110 msl |

**Table 1. b)** Geographical grid details used in the study region highlighted in yellow (For interpretation of the references to color in this figure, the reader is referred to the web version of this article).

| Grids | | | |
|---|---|---|---|
| 15.0 | 9 | 10 | 11 |
| 13.5 | 6 | 7 | 8 |
| 12.0 | 227 | 4 | 5 |
| 10.5 | 200 | 2 | 3 |
| 9.0 | 173 | 174 | 1 |
| | 75.0 | 76.5 | 78.0 |

**Table 3.** Planters' perception on the cutting-edge issues including drought and climate change affecting sustainability of cardamom farming (n=103)

| Cutting edge issues | Percentage perception | Ranking |
|---|---|---|
| Drought and climate change | 96.1 | (I) |
| Irrigation water availability and scarcity | 95.1 | (II) |
| Insect pests and disease problems | 66.0 | (III) |
| Unfavorable price | 59.2 | (IV) |
| Pesticide contamination in crops and soil environment | 37.8 | (V) |
| Water quality problems | 28.1 | (VI) |
| Shade level and forest degradation | 27.1 | (VII) |
| Topsoil loss and degradation | 15.5 | (VIII) |

# Ecological physiology of cardamom, coffee and black pepper

Key physiological parameters of cardamom, coffee and black pepper those are common to all cardamom-coffee hotspots in India are presented in Fig. 10. $A_{net}$ in *C. robusta* and *E. Cardamomum* have shown single peak curves during the day, while *P. nigrum* showed two-peak curves (Fig. 10a). But the time when the $A_{net}$ peak occurred was different between the crops, being at 1100 h for *C. robusta* and at 0900 h for both *P. nigrum* and *E. cardamomum*. The diurnal patterns of gs in two crops coffee (robusta) and small cardamom were showed one-peak curves, while *P. nigrum* showed two-peak curves. A midday depression of gs was exhibited in all three crops, but the stomata did not close entirely. The time when the depression occurred was 1100 h for cardamom and pepper and 1300 h for coffee. Midday depression of leaf $A_{net}$ is usually found in $C_3$ plants such as rice (Ishihara and Saitoh, 1987), and soybean (Huck et al, 1983). We also found midday depression of $A_{net}$ in the all $C_3$ crops (Fig. 10b), although it was not so typical. Many researchers have reported that the main cause for the reduction in photosynthetic rate was largely due to stomatal closure (Hirasawa et al. 1989; Wakabayashi et al. 1996). A close positive correlation between $A_{net}$ and $g_s$ ($r^2 = 0.776^{**}$, $r^2 = 0.723^{**}$ and $r^2 = 0.544^{**}$ for *E. cardamomum*, *C. robusta* and *P. nigrum* respectively) had indicated that the midday depression of $A_{net}$ in all three species might be due to stomatal closure (Fig. 10c). But the increase in $g_s$ was always procession by a decrease in $C_i$ in *C. robusta* and *E. cardamomum*, but in *P. nigrum* the increased $g_s$ was always accompanied by an increase in $C_i$ (Fig. 10d). The low $C_i$ values upon high $g$s values indicated that the midday depression of $A_{net}$ was not caused primarily by the lower $g_s$, but rather by non-stomatal factors in *C. robusta* and *E. cardamomum* and depression of $A_{net}$ was caused primarily by the lower $g_s$, relatively by stomatal factors.

Like many other tropical plant species *C. robusta*, and *E. cardamomum* experience a pronounced midday depression in net photosynthesis ($A_{net}$) and stomatal conductance (gs) under tropical Indian climatic conditions during summer. *P. nigrum* did show a slight recovery after midday depression in $A_{net}$ and gs but the overall pattern is different from the other two species investigated. These differences could be due to differences in leaf types with complex interactions with environmental variables. Similar differences in diurnal patterns were reported earlier for *C. robusta*, and *E. cardamomum* (Alagupalamuthirsola et al. 2018). The depressions in $A_{net}$ and gs could also be due to diurnal variation in leaf temperature (36–42°C) in all these crops, but the temperature variation during peak photosynthesis and depression is 3°C (37–40°C) in *C. robusta*, 1°C (38°C to 39°C) in *P. nigrum* and 6°C (36–42°C) in *E. cardamomum* during the days under observation. The diurnal changes in temperature and $A_{net}$ also shows that temperature variation may not have a direct effect on afternoon decline in $A_{net}$ in *C. robusta*, and *P. nigrum* but its *E. cardamomum* may have slight direct effect on $A_{net}$ during 0900 to 1300 h.

We observed the peak values of $A_{net}$ occurred at 1100 h for *C. robusta* and *P. nigrum* and at 0900 h for *E. cardamomum*. Associating with PPFD (Fig. 10b and Fig. 10e), it was shown that $A_{net}$ declined after 1100 h ($T_{leaf}$ 37.7$^{o}$C) in *C. robusta*, the 1st decline after 0900 h ($T_{leaf}$ 39.1 $^{o}$C) and the 2nd decline after 1500 h ($T_{leaf}$ 38$^{o}$C) in *P. nigrum* and also $A_{net}$ declined after 0900 h ($T_{leaf}$ 36.6$^{o}$C) in *E. cardamomum*, whereas the PPFD still increased higher than 1500 µmol $m^{-2}$ $s^{-1}$ between 1100 h and 1300 h (Fig. 10a). This is exactly the temperature at which Rubisco would be deactivated. The conditions with $A_{net}$ peak are in fact the optimal combination of multiple environmental factors for leaf photosynthesis. Between 0900 h and 1500 h, the ambient temperature was higher than 30°C. High temperature affects the photosynthetic functions of crop plants by its effects on the rate of chemical reactions and on structural organization (Pastenes and Horton, 1996). In $C_3$ plants, ribulose-1,5 bisphosphate carboxylase/oxygenase (Rubisco) activity is limited by the $CO_2$ concentration. As temperature increases, the affinity of the enzyme for $CO_2$ and the solubility of $CO_2$ decrease. Together with Rubisco deactivation with temperature increasing, $A_{net}$ declines at leaf temperatures greater than 32°C in $C_3$ plants (Crafts-Brandner and Salvucci, 2004). So, the effects of temperature on Rubisco activity without other compensation mechanisms could be a reason rather than for $A_{net}$ in *E. cardamomum* and *P. nigrum* being lower beyond 30°C and in *C. robusta* beyond 32°C. By comparing PPFD at 0900 h (928 and 1061 µmol $m^{-2}$ $s^{-1}$ in *E. cardamomum* and *P. nigrum* respectively) and 1100 h (1230 µmol $m^{-2}$ $s^{-1}$ in *C. robusta*) (Fig. 10a), we give evidence that leaf photosynthesis of cardamom and black pepper was less adaptive to high irradiance and atmospheric temperature than that of *C. robusta*.

Leaf temperature increased throughout the day until respective maximum values of 40.8°C, 38.7°C and 42.6°C and values of VPD 1.08, 0.95 and 0.36 mbar were reached in *C. robusta*, *P. nigrum* and *E. cardamomum* respectively (Fig. 10f). The decline in $A_{net}$ and gs was associated with high PPFD and substantial increase in VPD from 0900 to 1300 h in *P. nigrum* and *E. cardamomum*, and 1100 to 1300 h in *C. robusta*. The potential effects of leaf temperature on the diurnal pattern of the photosynthetic rates for a given temperature at saturation PPFD (> 900 μmol $m^{-2}s^{-1}$), the $A_{net}$ measured in the afternoon was always lower than that in the morning in *C. robusta* and *E. cardamomum*, but in *P. nigrum* it was higher at 1500 h than that of the morning. This shows that a circadian component was not essential for the development of a midday depression of $A_{net}$ and gs in *P. nigrum* which is apparent from the experiments in which the PPFD and VPD were reached high (Fig. 10f). However, in *C. robusta* and *E. cardamomum*, it appears that high PPFD and high VPD may not disturb the overall pattern of diurnal variation in $A_{net}$ and/or gs during entire day which in turn may have been governed by circadian components. Therefore, we presume that crops like *P. nigrum* grown under low VPD conditions (monsoon) when exposed to a relatively dry environment (summer) show strong stomatal response to dry air atmosphere with double peaked diurnal activity. In the case of *C. robusta* and *E. cardamomum* the circadian component like leaf folding mechanism to some extent endows the leaf with mechanisms that reduce the exposing area to the irradiance and conserve water without undergoing large stomatal changes. This may be the reason for the one peak response in *C. robusta* and *E. cardamomum*.

Leaves of all the three species would withstand much higher PPFD (up to 1600 μmol $m^{-2}$ $s^{-1}$) than their saturation limit (500 to 800 μmol $m^{-2}s^{-1}$) without damaging the photosynthesis significantly, when VPD was favourable. In *P. nigrum* the effect of high VPD was instantaneous and gas exchange rates remained low as long as high VPD was maintained. The gas exchange rates were improved only when VPD was lowered and results provided enough evidence for the dominant role of VPD in *P. nigrum*. In the second, the reduction in $A_{net}$ and gs in *P. nigrum* due to high VPD (40–50%) was higher as compared to that of high PPFD (10–20%) during 0900 to 1300 h. And also, reduction in $A_{net}$ and gs in *E. cardamomum* due to high VPD influencing (103%) than PPFD (48%) only during 0900 to 1100 h, after 1100 h *E. cardamomum* undergoes circadian leaf folding mechanism during midday to reduce the exposure to irradiance without undergoing large stomatal chances. However, in *C. robusta* it appears that high PPFD and high VPD may not disturb the overall pattern of diurnal variation in $A_{net}$ and gs which in turn may have been rather governed by circadian components like leaf folding mechanism to reduce irradiance exposure. It has been shown in trees *Acacia auriculiformis* (growing in foot hills of the WG) that as long as VPD was held constant, the photosynthetic capacity and stomatal conductance were almost insensitive to changes in temperature (in the range 27–38°C) and photosynthesis rate began to decline with increasing temperature only after threshold VPD was exceeded. In our observations the temperature variations were not large and a decline in photosynthesis set in only after a critical VPD had been exceeded. This threshold VPD may be different for different leaf types and may be influenced by growth conditions. Thus *C. robusta* might have a highest critical VPD of 9 mbar as compared to 4.45 and 1.78 mbar for *P. nigrum* and *E. cardamomum* respectively (Fig. 10f). From these observations it appears that leaves of *P. nigrum* and *E. cardamomum* are susceptible to light and/or VPD stress to a varying extent compared to *C. robusta* which was relatively less affected when exposed to the above-mentioned stress conditions.

The potential photosynthetic capacity of *C. robusta* leaves is relatively high (30 μmol$CO_2m^{-2}s^{-1}$) and could be even greater than that of *P. nigrum* and *E. cardamomu* (Alagupalamuthirsolai, et al., 2018; Murugan et al., 2009) and also other crops such as wheat and spinach (Martins et al. 2014a). However, their actual $A_{net}$ is relatively low (typically in the range of 4–11 μmol $m^{-2}s^{-1}$ at saturating light and current atmospheric [$CO_2$] when compared with many others tropical tree crops (DaMatta, 2004). Given these facts, it is clear that such a low $A_{net}$ is due mainly to large limitations to $CO_2$ diffusion from the atmosphere to the chloroplasts (Batista, et al., 2012). This is in good agreement with the low values of gs and gm (mesophyll conductance, i.e., the conductance to $CO_2$ from the intercellular air spaces to the chloroplast carboxylation sites). Such large diffusional limitations to $A_{net}$ suggest that *C. robusta* might benefit from increasing [$CO_2$] relatively more than *P. nigrum* and *E. cardamomum* with low diffusional limitations to photosynthesis.

*C. robusta* has evolved in shaded environments and its photosynthetic apparatus becomes saturated at relatively low PPFD (DaMatta, 2004). Therefore, when the plant is grown in open fields, leaves can absorb more light energy than can be used in photosynthesis, which could increase the probability of formation of highly reactive oxygen species (ROS) and triplet chlorophyll production. Under future climate warning as well as elevated [$CO_2$], more light energy is required to saturate photosynthesis (Ramalho, et al., 2013), thus a proportional lower energy level will be available to promote cell oxidative conditions; furthermore, the anticipated lower production of ROS (e.g., hydrogen peroxide) via decreases in photorespiration rates under enhanced [$CO_2$] should also contribute to decrease the oxidative stress and, ultimately, promoting a better physiological and agronomic performance under elevated [$CO_2$]

The differences in $WUE_i$ during 0700 to 1100 h, 0900 to 1500 h and 1100 to 1300 h were mainly due to their specific ability to maintain $A_{net}$ rather than changes in transpirational water loss in *P. nigrum* (E), *E. cardamomum*, and *C. robusta* respectively (Fig. 10g & h). Differences in $WUE_i$ during 1100 to 1500 h and 0700 to 0900 h were mainly due to their specific ability in changes in E rather than their capability to maintain $A_{net}$ in *E. cardamomum* and *P. nigrum* respectively and also during 0700 to 1100 h and 1300 to 1700 h in *C. robusta* that showed more influence of *E. cardamomum* than $A_{net}$. The results of changes in $WUE_i$ of *C. robusta* and small cardamom which were mostly influenced by E during diurnal pattern. The reason that *C. robusta* avoids heat load deposition on leaves from 1100 h onwards by doing partial leaf folding mechanism to reduce transpirational water loss. Clearly, it is a tendency of higher $WUE_i$ in *C. robusta* plants, providing a promising mechanism for the maintenance of productivity, and hence, fitness advantage in water deficit environments (Farquhar et al. 1989). In combination with gas exchange, it can be suggested that higher $WUE_i$ resulted primarily from the maintenance of high photosynthetic capacity and down-regulation of stomatal conductance and transpiration controlling the internal plant water status (Scartazza, et al. 1998).

Leverenz et al. (1990) reported that a decrease in maximum carboxylation rate occurs at the primary stage of photoinhibition. In this study, Fv/Fm of three species decreased with the increased PPFD in the morning, then recovered during the afternoon when PPFD decreased (Fig. 10i). These reversible changes suggest that a down-regulation of PSII might happen in photosynthetically active leaves. This type of response may reflect a protective mechanism in avoiding photodamage to the photosynthetic apparatus under excess irradiance (Demmig-Adams and Adams, 1992). For leaves under high irradiance at midday, along with depressed photosynthetic rates, the excessive excited energy must be safely dissipated; otherwise, the photosynthetic system will suffer photoinhibitory damage unless compensatory mechanisms alleviate photoinhibition are operational (Mattos et al. 1997; Graßes et al. 2002). The maximum PSII efficiency $F_v/F_m$ is widely used as an indicator of photoinhibition (Ort and Baker, 2002). In this study, reversible change in Fv/Fm was found in black pepper and cardamom during the day, suggesting photoprotection rather than photodamage occurred. The decrease in $F_v/F_m$ is likely due to the reversible inactivation or downregulation of PSII, rather than the photodamage to PSII or loss of D1 protein (Demmig-Adams et al. 1996).

# Conclusion

Our results from the RCP scenario analyses for the hot spots give indications that future air temperature as well as precipitation levels will vary extremely. An increase in air temperature by 8ºC along with 80% incidence or disease in precipitation levels likely to cause significant changes in all physiological parameters including WUE of all these species (coffee, cardamom and black pepper). Therefore, the growth, development and yield of cardamom, coffee and black pepper in these hot spots would be impacted negatively warranting prioritation of climate mitigation and adaptation strategies. Only then the livelihoods of Milhous of farmers and labors can be protected

# Declarations

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## Author contributions

M. Murugan and A. Anandhi developed the methodology and conceived the work. R. Ravi, K. Ashokumar, K.S. Krishnamurthy and M.K. Dhanya collected and complied data. M. Murugan, A. Anandhi and M. Alagupalamuthirsolai analysed the data and wrote the manuscript.

## Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

## Code availability

Code is available from the author upon request

**Consent to participate:** The manuscript has been read and approved by all named authors and there are no other persons who satisfied the criteria for authorship but are not listed. The order of authors listed in the manuscript has been approved by all of the authors.

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**Conflict of interest:** The authors declare no competing interests.

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# Table

Table 2 is not available with this version

# Figures

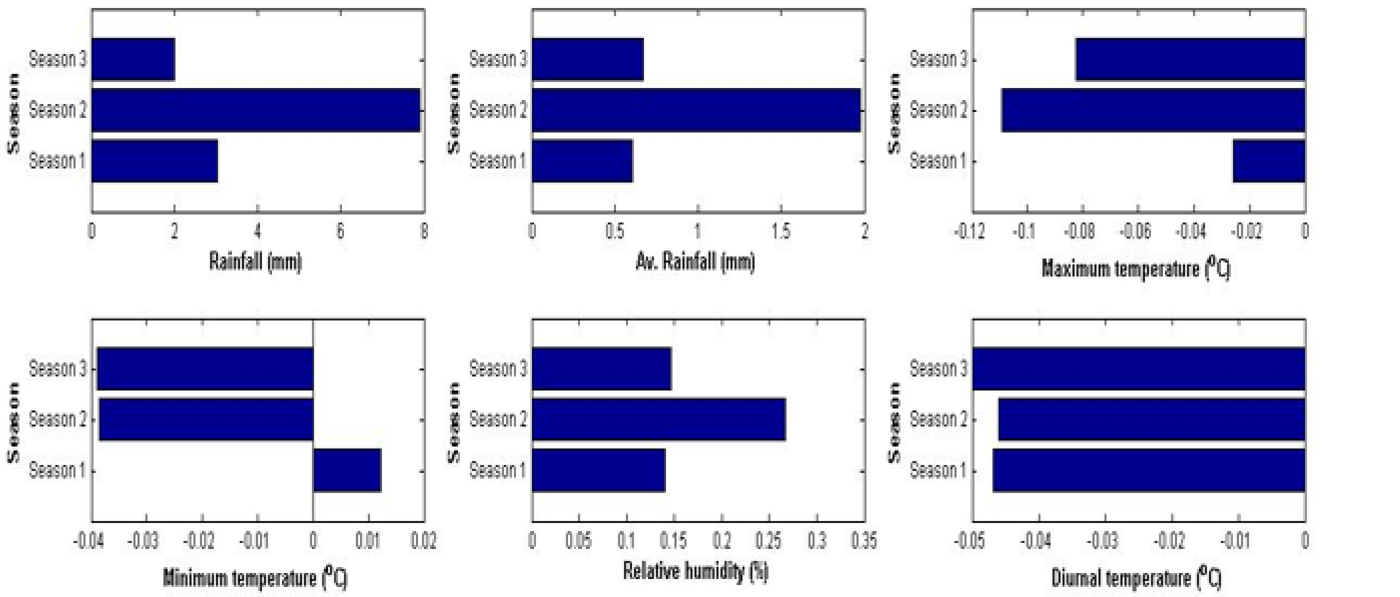
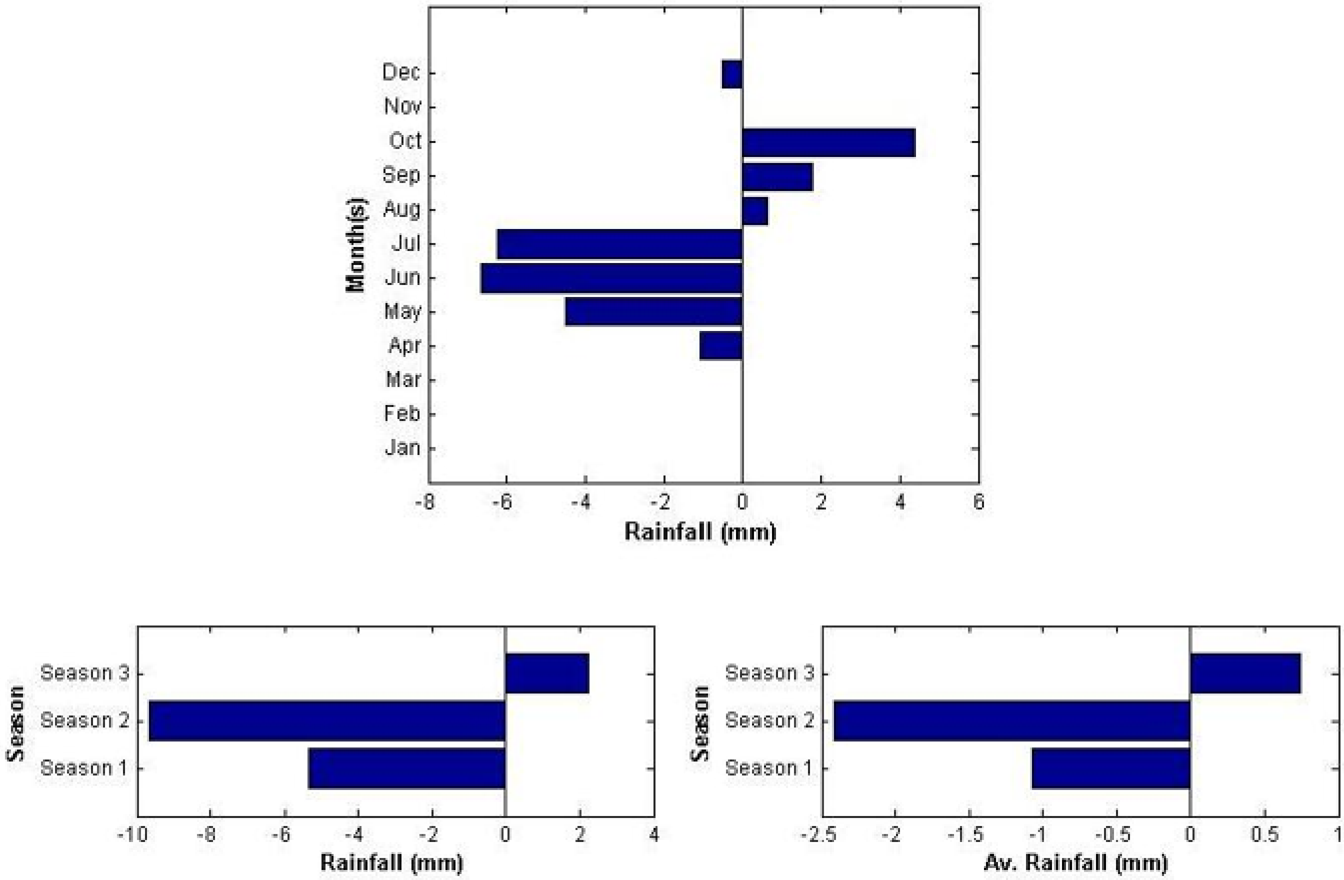


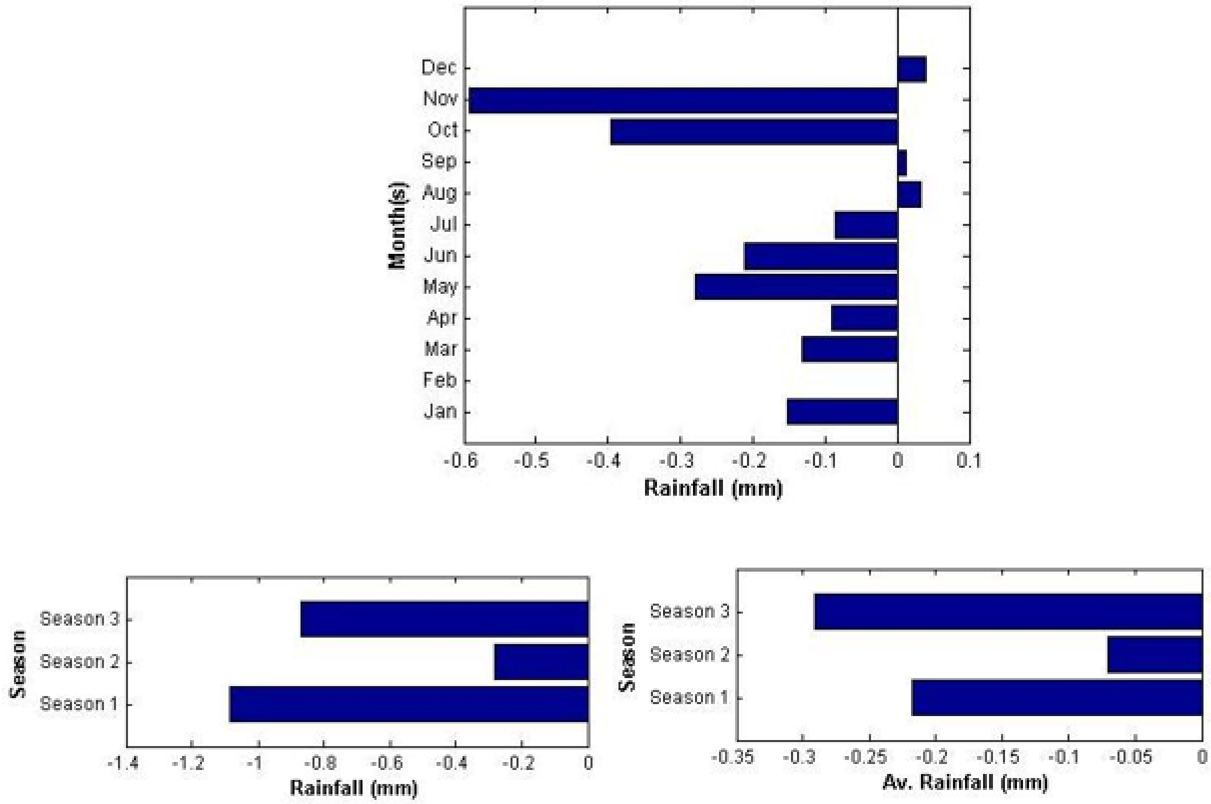

**Figure 1**

Sen slopes of trends in climatic variability in temperate UPH, Tamil Nadu



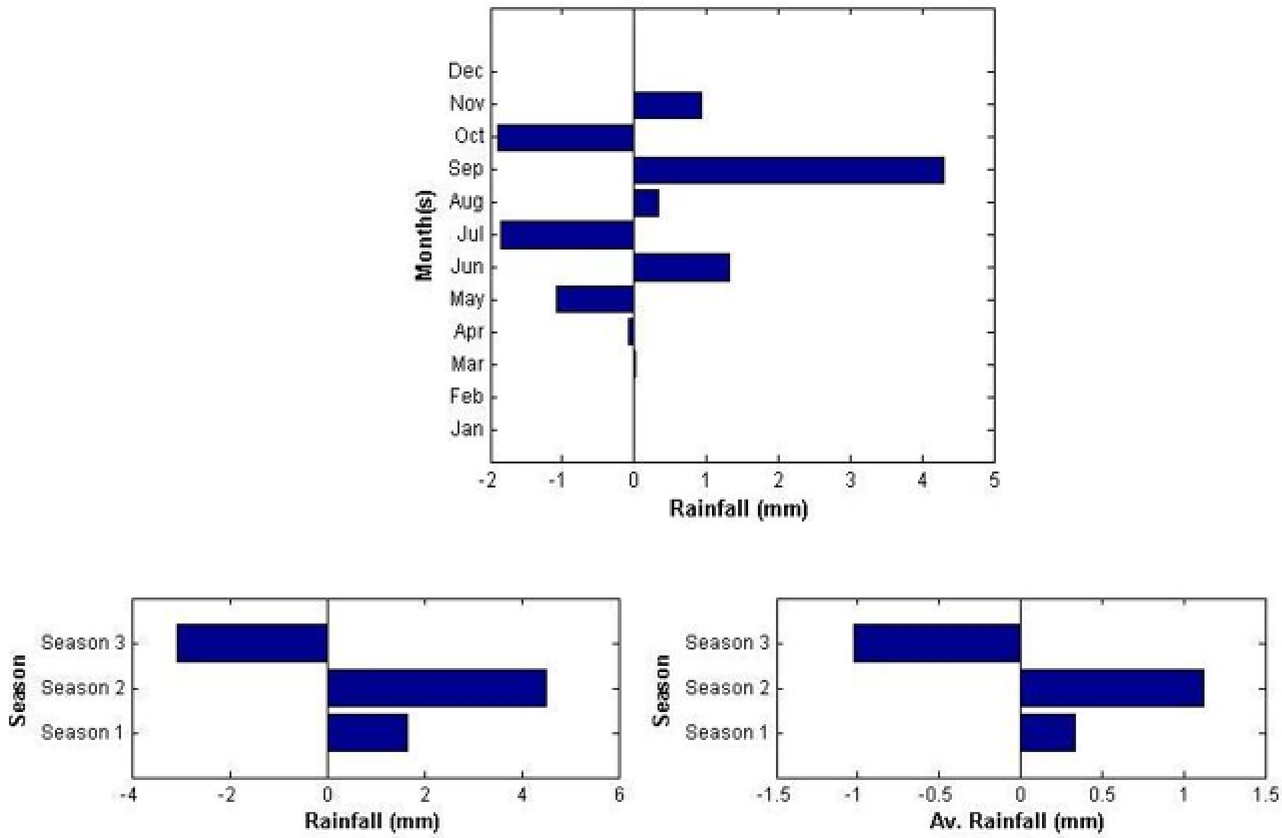

## Figure 2

Sen slopes of trends in climatic variability in CH, Kerala



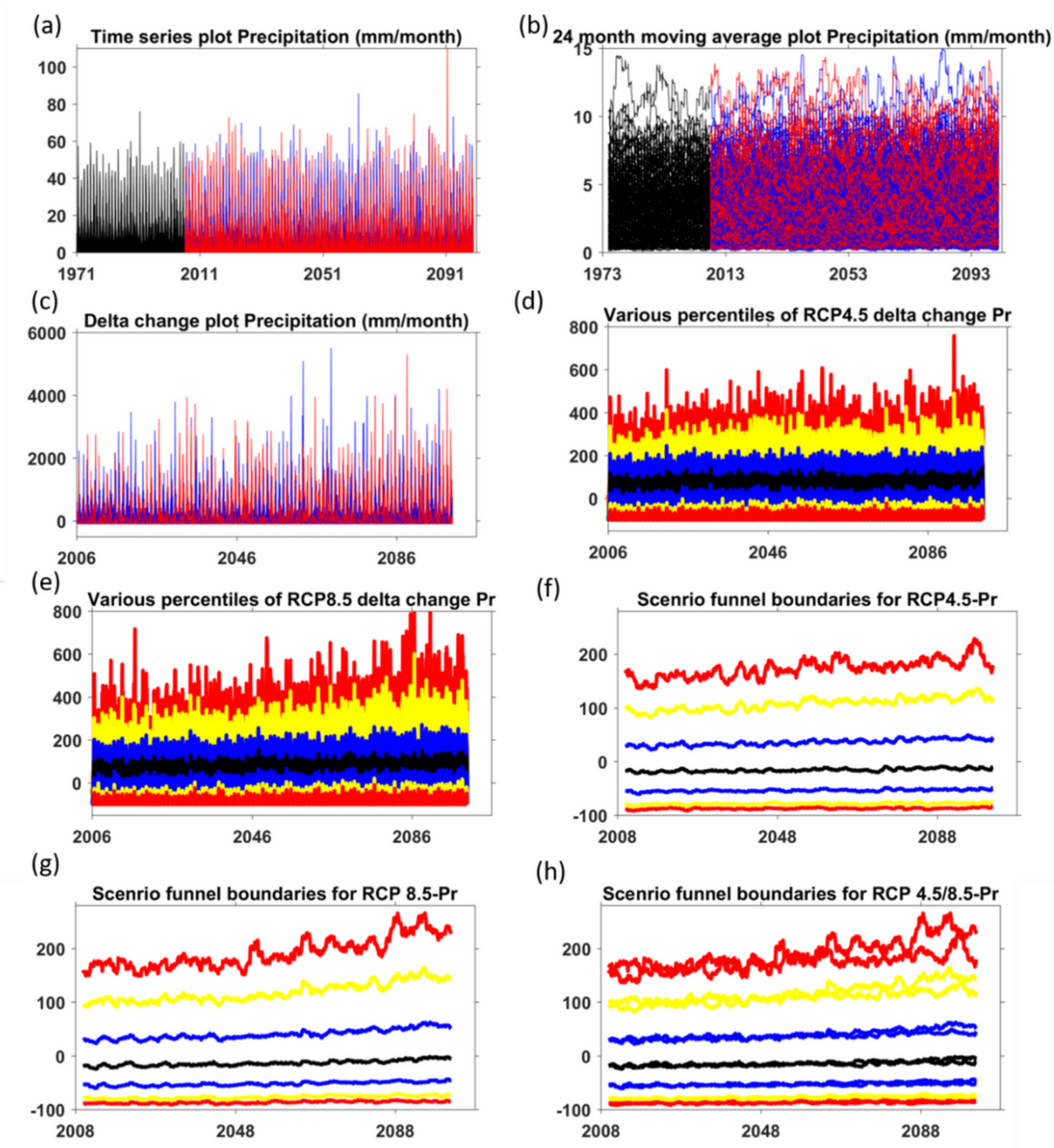

## Figure 3

Sen slopes of trends in climatic variability in LPH (Manalur), Tamil Nadu




## Figure 4

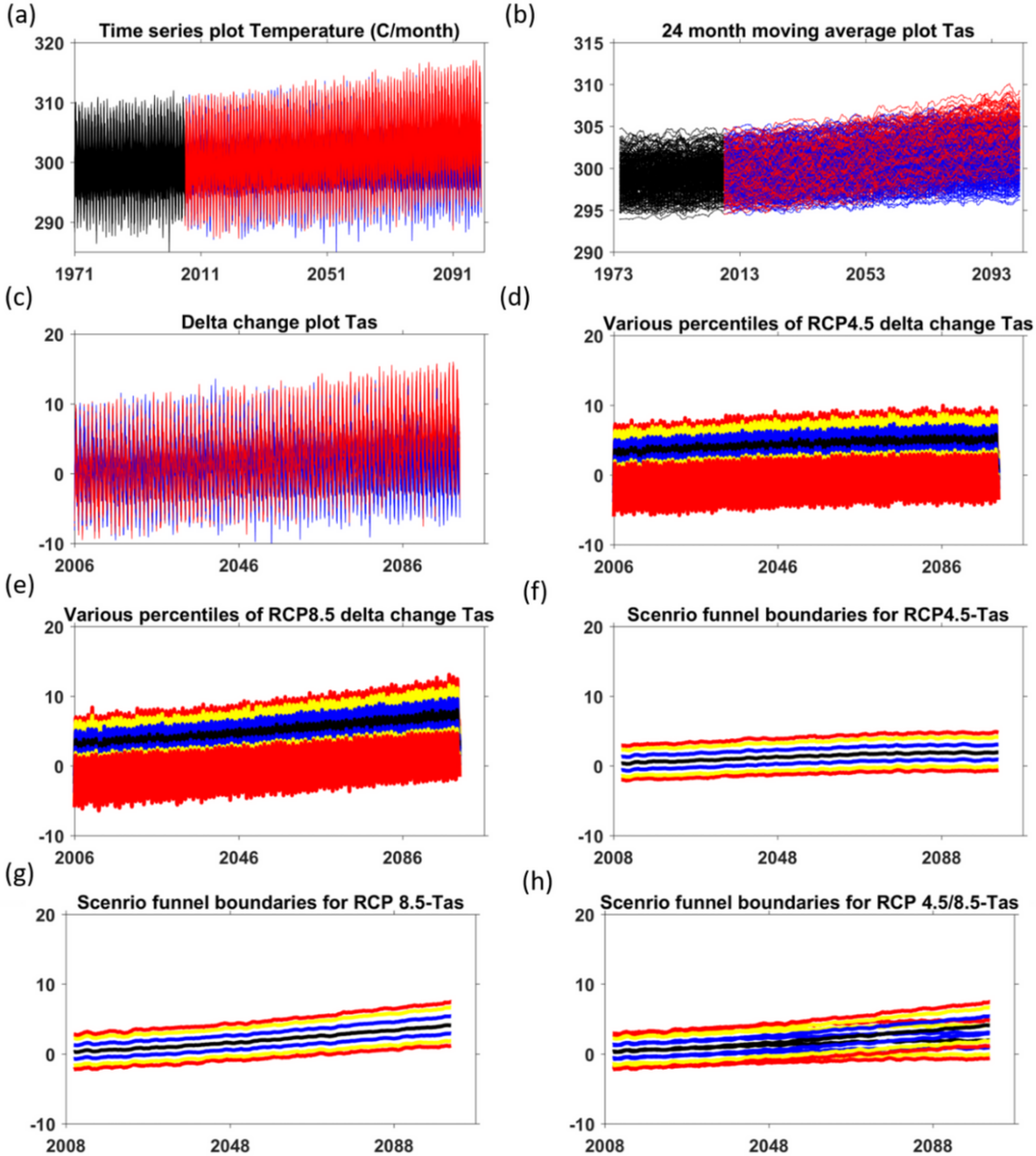
Sen slopes of trends in precipitation variation in KH, Karnataka




## Figure 5

The plot of various steps in developing the scenario funnel for precipitation (Pr, a to h) by data-analysis, (a) time-series plot of raw precipitation data, (b) time-series plot of 24 month moving precipitation data, (b) time-series plot of 24 month moving average precipitation data, (c) time-series plot of delta change estimated for precipitation, (d) various percentile values for RCP 4.5 for precipitation (red: 5th, 95th; yellow:10th, 90th, blue: 25th, 75th, black: 50th percentiles), (e) various percentile values for RCP 8.5 for precipitation (red: 5th, 95th; yellow:10th, 90th, blue: 25th, 75th, black: 50th percentiles), (f) Developing scenario funnel boundaries for RCP 4.5 from 24 month moving average of the percentiles (red: 5th, 95th;

yellow:10th, 90th, blue: 25th, 75th, black: 50th percentiles), (g) Developing scenario funnel boundaries for RCP 8.5 from 24 month moving average of the percentiles (red: 5th, 95th; yellow:10th, 90th, blue: 25th, 75th, black: 50th percentiles), (h) scenario funnels for precipitation. In a, b, c, red and blue color represents the RCP 8.5 and RCP 4.5 respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).




## Figure 6

The plot of various steps in developing the scenario funnel for average surface temperature (T as, a to h) by data-analysis, (a) time-series plot of raw temperature data, (b) time-series plot of 24 month moving temperature data, (b) time-series plot of 24 month moving average temperature data, (c) time-series plot of delta change estimated for temperature, (d) various percentile values for RCP 4.5 for temperature (red: 5th, 95th; yellow:10th, 90th, blue: 25th, 75th, black: 50th percentiles), (e) various percentile values for RCP 8.5 for temperature (red: 5th, 95th; yellow:10th, 90th, blue: 25th, 75th, black: 50th percentiles), (f) Developing scenario funnel boundaries for RCP 4.5 from 24 month moving average of the percentiles (red: 5th, 95th; yellow:10th, 90th, blue: 25th, 75th, black: 50th percentiles), (g) Developing scenario funnel boundaries for RCP 8.5 from 24 month moving average of the percentiles (red: 5th, 95th; yellow:10th, 90th, blue: 25th, 75th, black: 50th percentiles), (h) scenario funnels for temperature. In a, b, c, red and blue color represents the RCP 8.5 and RCP 4.5 respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

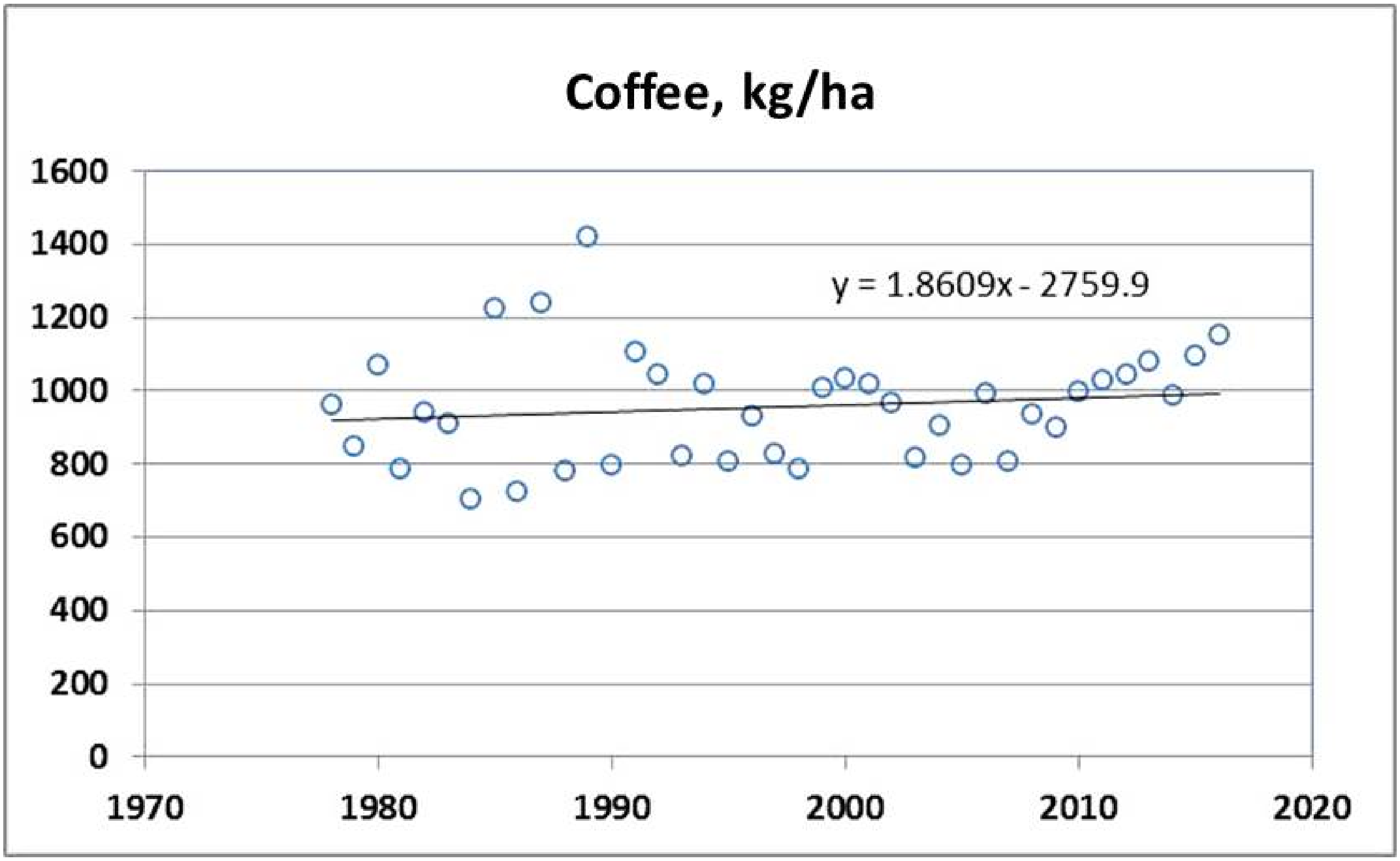



**Figure 7**

Coffee productivity trend for the Kodagu hills (Karnataka)

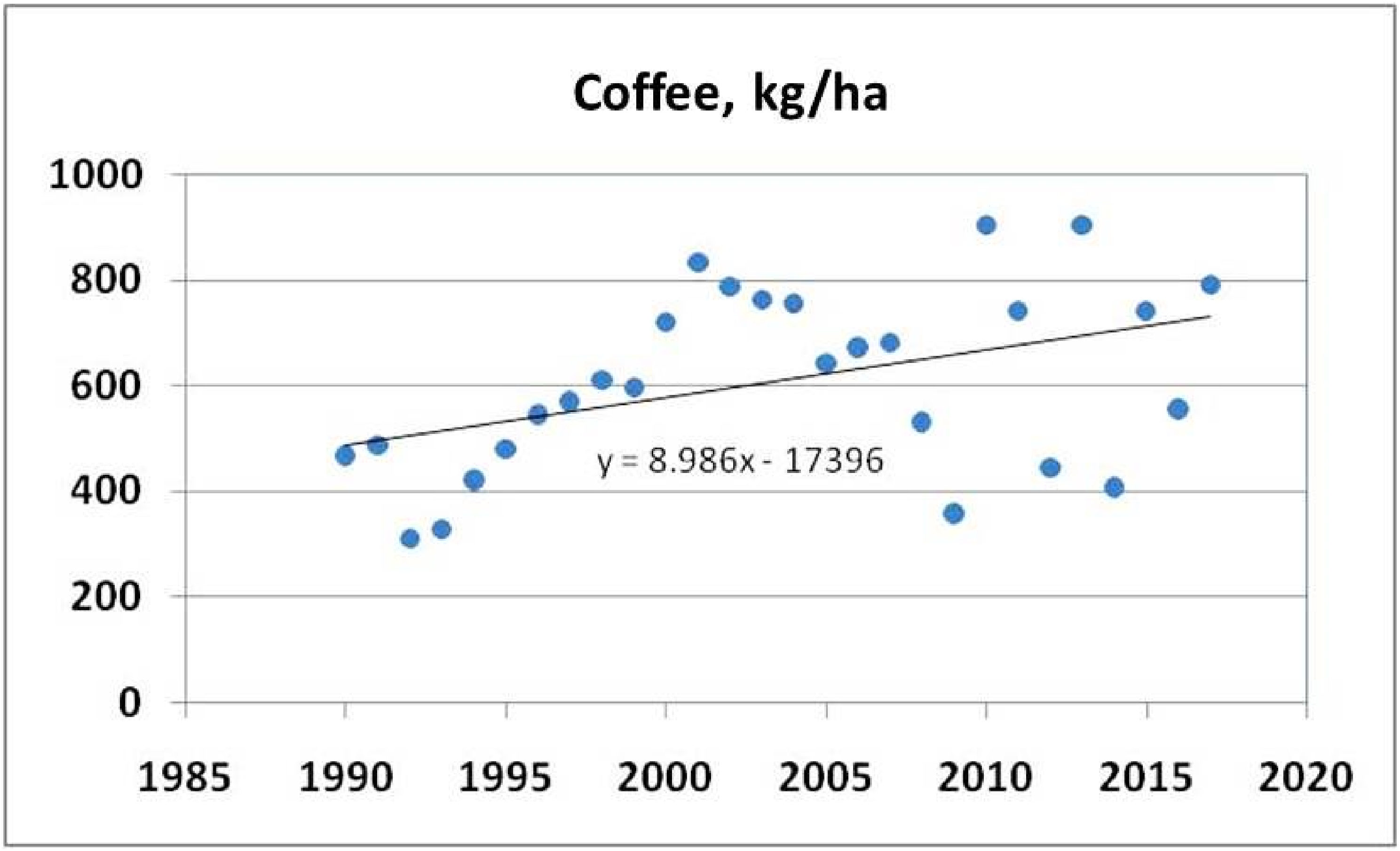



Figure 8

Coffee productivity trend for the Cardamom hills (Kerala)

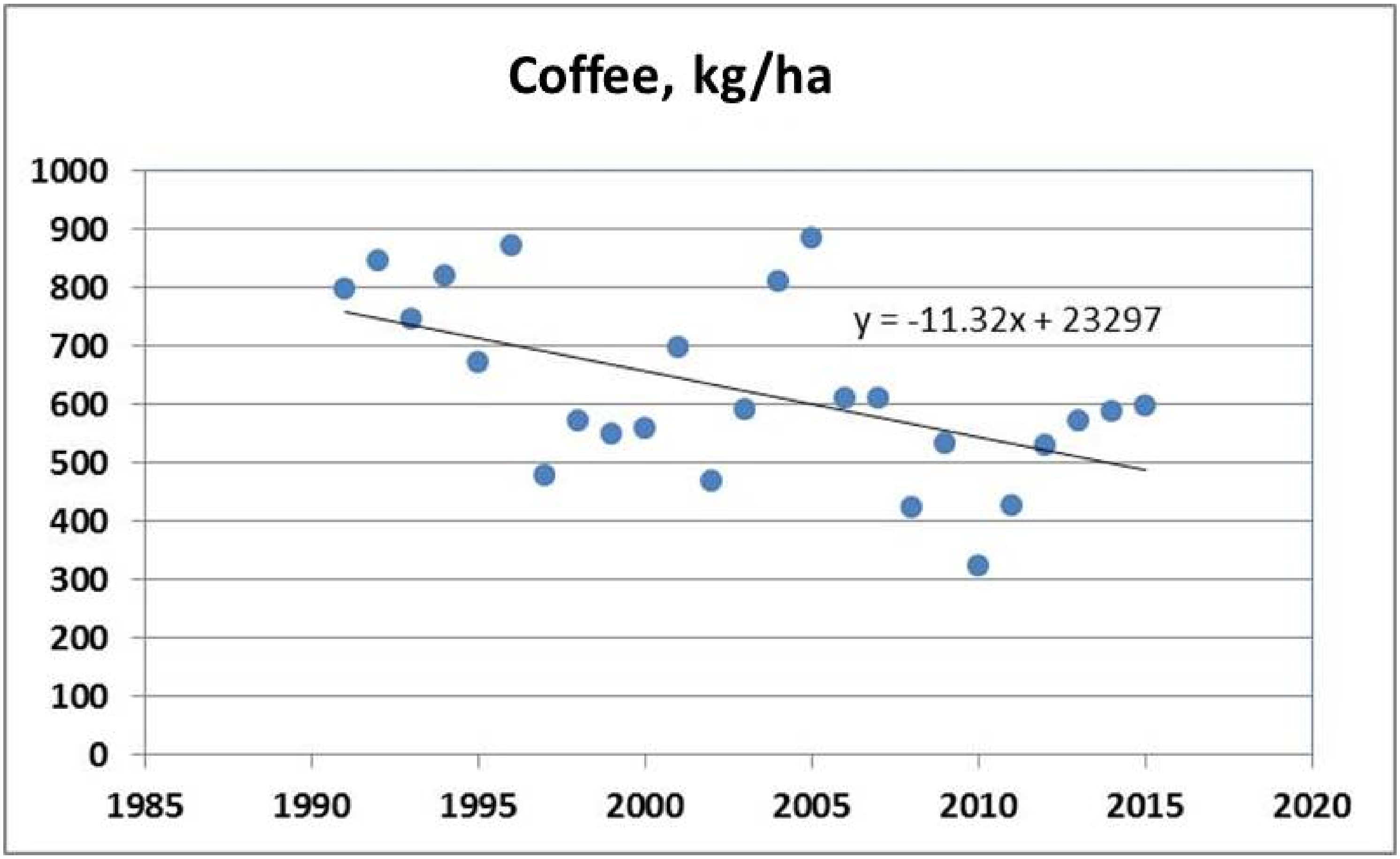
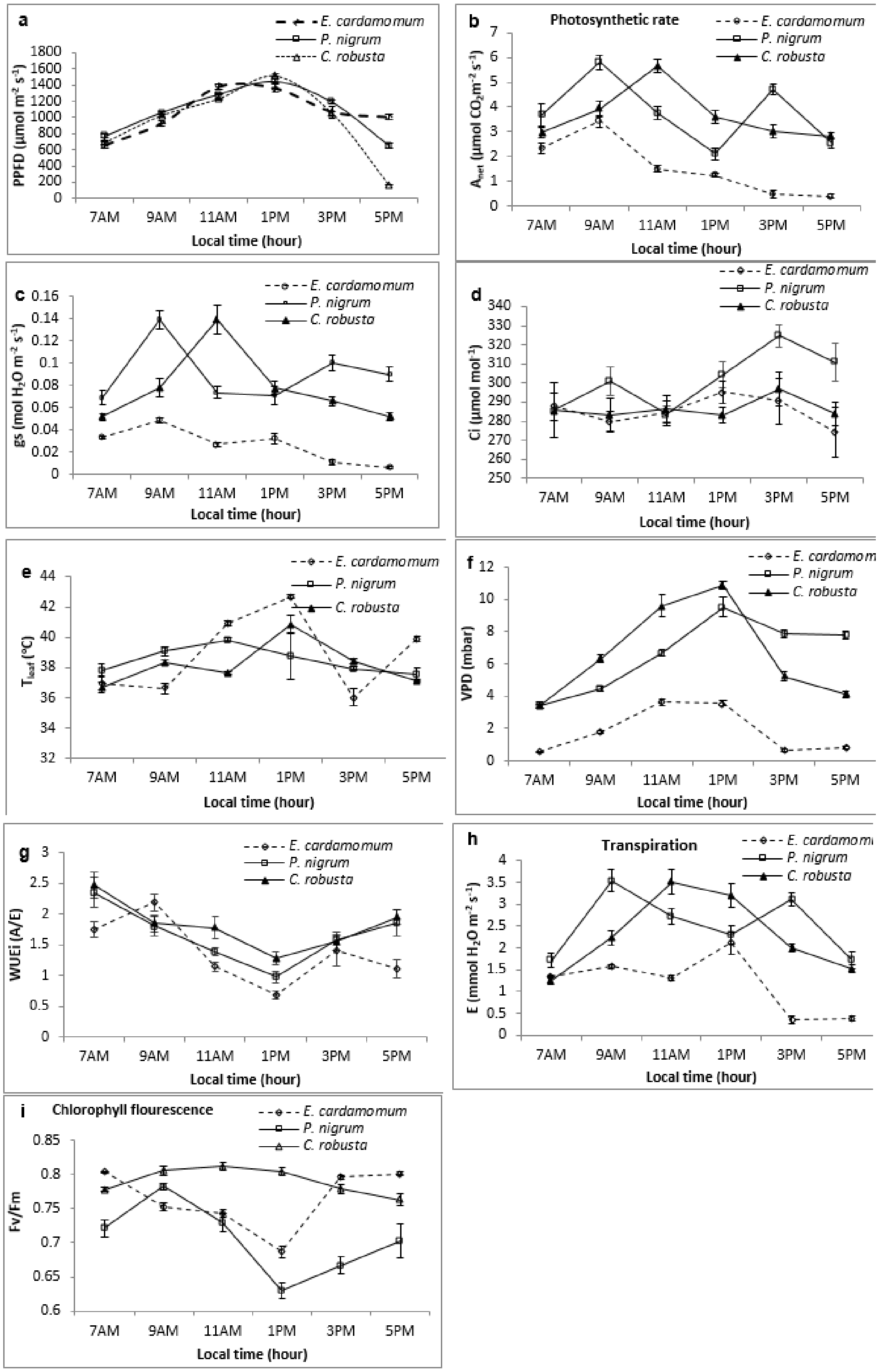



**Figure 9**

Coffee productivity trend for the Lower Pulney hills (Tamil Nadu)



## Figure 10

Eco-physiological parameters of cardamom, black pepper and coffee

# Supplementary Files

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