Title
Coffee and Climate Change in a Biodiversity Hotspot: The nexus of agriculture, climate adaptation and biodiversity conservation in Kerala, India.

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The nexus of agriculture, climate adaptation and biodiversity conservation in Kerala, India.

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Executive Summary

It is predicted that approximately half of the global land area currently used for coffee production will be unsuitable for this purpose by the year 2050 due to climate change.[1] This has substantial social implications as an estimated 125 million people worldwide depend on coffee production for their livelihoods.[2] While this constitutes a global problem, the solutions are likely to be locally derived and vary with environmental, economic, and cultural factors on a regional scale. The same studies that project these large-scale shifts in coffee-growing suitability "call for approaches at the local scale to help farmers to adapt to climate change." [3] In this context, the nexus of coffee, agriculture, and climate change is explored with the coffee-growing region of Wayanad in Kerala, India as a case study. History of the coffee industry in South India is introduced, along with a brief description of the contemporary global coffee market. Local weather in Wayanad is examined quantitatively in reference to global climate trends. Finally, a review of implications, policy options, and adaptation strategies is put forth. Emphasis is placed upon the importance of conscientious consumer choice and the implementation of sustainable agricultural practices as the most effective ways to build climate resilience into the global coffee supply chain.

Introduction

"The ecological responsibility should not lie entirely on the farmer's shoulders. It is the responsibility of society, and the whole world."

This is what Farmer Prasanth said to me as we trekked through his property in the tropical mountains of Kerala, along the southwestern coast of India. Prasanth's family has been growing coffee on his 10-acre property for over 70 years. "These plants here are over 50 years old," he says affectionately as he runs his fingers through the leaves of the tree next to him. Coffee plants of this age are certainly past their prime in terms of productivity, but they bear fruit nonetheless, and most farmers in this region lack the economic resources to uproot older trees and replant.

The state of Kerala, which encompasses the Western Ghats mountain range and the famed Malabar Coast in Southern India, is one of the most ecologically rich regions in the world. The mountains are designated by UNESCO as a World Heritage Site, and by the International Union for Conservation of Nature (IUCN) as one of the Top 10 most important "Biodiversity Hotspots" on Earth. The region is home to almost 6,000 known plant species, over half of which occur nowhere else in the world.[1] On top of this, it is the most densely populated state in India, home to over 35 million people.[2] (For comparison, Kerala is less than one-quarter of the size of Florida, which has a population of only 22 million.)

Here in the mountainous region, the vast majority of people are farmers. In addition to having an astounding diversity of wild species, the state of Kerala is home to a huge variety of agricultural crops. According to a recent study, over half

(54.8%) of the total area of Kerala is actively cultivated farmland, and at least 127 different crop species are grown across the State. Most farms are "homestead" or "home-garden" style, which according to University of Kerala Botanist N. M. Nayar are "intimate multistory combinations of various trees and crops… They provide ecological and socioeconomic sustainability. "[3] This multi-species agroforestry style of farming has been used in India for millennia.

Needless to say, this high-density collision of human life, vibrant ecology, and agricultural diversity creates a hotspot of cultural richness and human-wildlife interaction. Prasanth, like many people in the region, practices a form of Hinduism, in which nature plays a prominent role. We were on the way to a sacred grove that was tucked away in the hills towards the back of his property. Sacred groves, or *Tapovan* as they are known in the local language, have been around for millennia in the Hindu tradition. The groves can range in size from an area of multiple acres to a single tree, and they are revered across India as places of worship, penance, and sanctuary for local deities.[4]

"Even the old, very old generations knew the importance of the forests," Prasanth said to me as we hiked the final leg of the trail to an enormous banyan tree at the top of the hill. "These groves have been protected for many thousand years. Now many types of trees, rare trees, you can only find them here. It is very good luck to have these groves on your land. Even the most greedy farmers won't touch them."

I smiled with anticipation as we approached. The grove on Prasanth's farm was very small, maybe forty square feet, only big enough for one tree and a handful of understory shrubs. The tree was huge, over eighty feet high, and had a dense canopy of broad emerald leaves. Among its twisting roots was a scattering of statuettes and oil candles, and the base of its trunk was scarred with lampblack.

"This grove is guarded by *nagas*," Prasanth said in a hushed voice. "Snake guardians." He held his arm outstretched in front of him, turned his palm upward, and curled his fingers as if grasping at the air. "Feel how much cooler it is here."

Indeed, even though the grove was tiny, the air was at least 5-10 degrees cooler than the surrounding farm. The soil was different too; the moist loam was spongy underfoot and insects scuttled among a thick layer of leaf litter. Outside the grove, the soil was compact and hard, and rivulets of erosion scoured the bare surface.

"The Swaminathan Institute is doing good work here," said Prasanth. "Keeping the trees alive. This will be good for future generations."

I was here in Kerala at the invitation of the M.S. Swaminathan Research Institute, an organization that works with smallholder farmers throughout India to implement better farming practices. Also known by the acronym MSSRI, the Institute was founded by agricultural scientist Dr. Swaminathan in 1988 and has been working in this region of Kerala since 1997. Now a large organization, the Institute has offices all over South India and is leading an astounding number of projects, from operating Botanical Gardens and Knowledge Centers where locals can learn about native edible and medicinal plants and take seedlings home with them, to constructing rainwater cisterns for villagers who lack access to clean drinking water.

As a graduate student researching changes in the Indian Monsoon and how coffee farmers are adapting to these changes, I jumped at the chance to visit. Here in Kerala, MSSRI is working with the local and federal government to provide stipends for coffee farmers to keep trees on their properties. While the sacred *Tapovan* groves are protected by ancient tradition, other forests in Kerala are being lost at an alarming rate. In the past ten years, new large-scale corporate coffee farms in Brazil and Vietnam have sprung up from seemingly out of nowhere. In addition to causing massive deforestation as old-growth rainforests are cleared to make room for these large farms, the recent surge in supply is driving coffee prices to unprecedented lows, from $2.88-per-pound in 2011 to, as of my time in Kerala in May 2019, a mere 95 cents.[5]

This is forcing small, traditional farmers to find other ways to squeeze more income out of their land. The average size of land holding in Kerala is a mere 0.27 ha, about twice the size as the average single-family home in an American suburb.[6] Farmers already cannot feed their families on such a small amount of land, and most work other small jobs to make ends meet. According to Prasanth, a single rosewood tree can fetch 70,000 rupees (about $1,000 USD) at market, so for farmers who have trees on their land, harvesting timber can be an extremely tempting way to get some quick cash. But this can lead to devastating long-term effects, as removing trees causes both the air and the soil to become hotter and drier.[7] Now there is growing concern that this trend will threaten the very ability for farmers to grow coffee at all in the not-so-distant future.

"It is hard not to be greedy," Prasanth says. "I can survive, growing coffee without cutting the trees. But my neighbor has a car. He has an apartment in the city, and his children go to better schools. I have pressure from my neighbors, and my family also. They call me crazy for keeping the trees. There is an ancient saying here: When your stomach is not full, you cannot hear."

History and Background

Although legends of humans using coffee in Ethiopia date back as early as 875 A.D., the earliest verifiable evidence of human coffee consumption occurs in Yemen in the 15th century.[1] At this time, it was illegal to bring unroasted coffee out of Arabia, and strict measures were taken to ensure that viable coffee seeds did not leave the country. The birth of coffee production in India is attributed to the Indian Muslim saint Baba Budan, who, on his return from a pilgrimage to Mecca, allegedly smuggled seven coffee beans out of Arabia by hiding them in his beard.[2] In 1670 he planted these seeds in Karnataka, and cultivation soon spread throughout the state and into neighboring regions.

The first large-scale plantations arose with British colonization and spread rapidly throughout South India, fueled by increasing demand for export to northern latitudes. The proliferation of coffeehouses in Western Europe during this era proved to have substantial social consequences. Also known as "Penny Universities" since the price of entry and a cup of coffee was commonly one penny, coffeehouses in 17th century Britain came to play an important role in social and political discourse. In a society with such a rigid socioeconomic class structure, coffeehouses were unique because they were one of the only places frequented by customers of all classes.[3] Thus they became popular establishments for discourse and debate, open to all classes and unfettered by the structure of academic universities. Intellectuals found in "the hot black liquor a curious stimulus quite unlike that produced by fermented juice of grape."[4] English coffeehouses "provided public space at a time when political action and debate had begun to spill beyond the institutions that had traditionally contained them," and because of this, are widely accepted as playing a significant role in birthing the age of Enlightenment in Europe.[5]

While coffee was bringing the Enlightenment to Western Europe, the commodity was having opposite effects in the regions where it was being produced. In India, the age of British plantations was rife with suffering and oppression, as slavery and forced labor were common practice. Historical research reveals that "during Europe's industrial revolution and rise of bourgeois society, slavery, coffee production, and plantations were inextricably linked."[6] Historical records indicate that in the 1830s, the East India Company held over 247,000 slaves in Wayanad the Malabar coast alone.[7] Even after slavery was officially abolished in 1861, so-called "agricultural slavery" and indentured labor on plantations continued.[8] According to historical accounts, indentured laborers were treated almost identically as they were during the height of slavery.[9] To this day, an estimated 18.3 million people in India and 46 million people worldwide live in conditions of modern de facto slavery, such as bonded labor, human trafficking, and forced marriage.[10]

The global coffee market has always been volatile. Plagued by unpredictable harvests, susceptibility to weather events, and massive disease outbreaks, regional coffee production has risen and fallen dramatically over the centuries. For example, in the late 19th century in Sri Lanka an outbreak of the fungal pathogen known as "coffee rust" caused 90 percent of area under coffee cultivation on the island to be abandoned.[11]

This past century has been no different for India. As the Great Depression affected coffee exports around the world in the 1930s, the Coffee Board of India was established to protect farmers and promote consumption of coffee. The Coffee Board of India, run by the federal government's Ministry of Commerce and Industry, pooled farmers' coffee for export at a set price. This provided price stability for farmers but also eliminated incentives to improve quality.[12]

From 1991 – 1996 a series of economic reforms relegated the coffee market in India entirely to the private sector.[13] Immediately thereafter, the price of coffee fell from its 1997 levels of around $2.50 per pound to a staggering 45 cents per pound in 2002, the lowest it has been in over fifty years.[14] India was not alone in this plight. While certainly not the only cause of financial insecurity among farmers, the spread of neoliberalism and free trade in the global commodity market has historically been associated with large increases in price volatility and overall downward trends in price, which has had deleterious effects for small-scale producers who depend on these markets for their livelihoods.[15] Especially in the 1980s and 1990s, growth and consolidation among multinational commodity traders led to a relative loss of market power among producing nations, while foreign pressure from international donors forced many of those nations to privatize their commodity export authorities against their own best interests.[16] This has led to income instability and poverty for many coffee farmers around the world.

The coffee farmers of Kerala are facing many of the same challenges that currently plague coffee farmers all over the world. In recent years the global price of coffee has fell drastically from $2.88-per-pound in 2011 to 93 cents-per-pound as of May 2019.[17] While maintaining its downward trend over the past decade, the price continues to fluctuate wildly, making it impossible for farmers to budget their yearly expenses. It is not unheard of for the price to even dip below an individual farmer's production costs, leaving powerless farmers forced to sell their harvest at a loss, or let it spoil in the fields and get nothing at all.

How is it possible that coffee farmers are selling their harvest for less than what it cost them to produce it? While this seems paradoxical to the very basis of economics, it is a common situation facing farmers of many different cash crops, where prices are determined by what are called "buyer-driven supply chains." While many factors go into the creation of buyer-driven supply chains, some of the few largest factors are discussed below.

- **Large numbers of small-scale producers.** Smallholder farmers are often forced into commodity markets by the need for cash and absence of alternative livelihood options. This means it is difficult for farmers to organize and exercise bargaining power over a small group of highly organized and extremely powerful corporate buyers. Because of this, farmers are forced to accept whatever price the buyers offer them.

- **Deregulated markets.** Many governments and international organizations used to set minimum prices for commodities such as coffee to protect farmers from price fluctuations. While these protections still exist for farmers within the USA and EU, many other nations have dismantled these protections in recent decades due to political pressure from large corporations who stand to benefit from such deregulation.

- **High barriers of entry.** For crops that are traded internationally, such as coffee, the equipment and infrastructure needed to process and export such commodities are much too expensive for smallholder farmers to acquire themselves. This leaves farmers no choice but to sell their harvest to whoever is willing to purchase it.

All this to say, farmers do not have the capacity to determine the price they get for their own products. Prices are driven by market conditions, speculation, futures contracts, and corporate interests who control the majority of world-market shares. With the growth of powerful commodities traders and the liberalization of international markets, prices for coffee and incomes for farmers have reached historic lows. This has led to an increasingly tenuous existence for those who already struggle to get by.

Historically, coffee cultivation consisted of only one plant species, *Coffea arabica*. Today, *Coffea arabica* still makes up most of the world's coffee production (about 70%), but cultivation of another species, *Coffea canephora,* also known as robusta coffee, is growing due to its higher levels of hardiness and productivity.[18] In addition, a very small amount of a third species *Coffea liberica* is grown. Although modern coffee production is currently limited to the scope of these three species, a large diversity of subvarieties and hybrids are grown throughout the world, each with their own unique flavors and characteristics.

Coffea arabica is widely lauded as having the best cup quality, and consistently fetches a higher price on the global commodity market. It also tends to grow better in slightly shaded conditions, making it conducive to traditional intercropping methods. In India, *Coffea arabica* is usually grown under the shade of other cultivated trees, such as jackfruit and areca nut, or under the shade of native forest trees, which are used to support vines of black pepper.[19] In the understory below the coffee plants ginger, clove and turmeric are grown. In addition to sustaining families of farmers for generations, a recent study has shown that these multispecies farms support much higher levels of animal biodiversity than conventional monocultures, and that they sequester soil carbon at the same rate as surrounding rainforests.[20]

However, the rise of *C. canephora* as a cash crop has changed things in Kerala. Due to its higher yields and tolerance to pests such as coffee rust *C. canephora* plantations have replaced multispecies *C. arabica* farms over huge swaths of India in recent decades. Today, nearly 80% of coffee grown in Wayanad and surrounding regions is *C. canephora*.[21] Since this robusta species prefers full-sun conditions, this shift away from *C. arabica* is associated with the removal of shade trees and a proliferation of full-sun monoculture coffee plantations. This has had substantial consequences for biodiversity, erosion, watershed management, and other ecosystem services.[22]

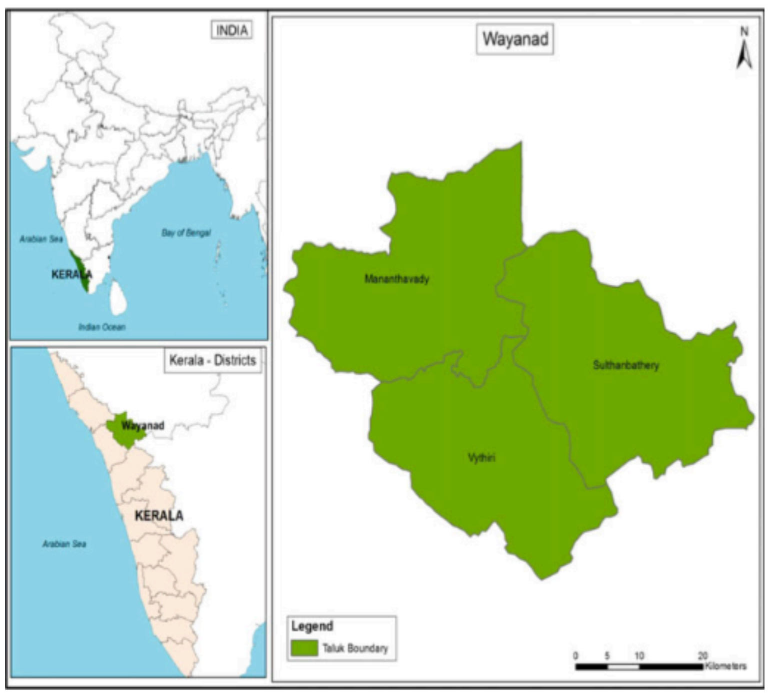
This has the potential to negatively impact the small amount of *C. arabica* that remains in Kerala. Studies indicate that deforestation can lead to a hotter and drier local climate.[23] *Coffea arabica* is a finicky plant, thriving in a narrow temperature range between 18˚ - 21˚ Celcius.[24] It follows that this pattern of tree removal could lead to conditions in Kerala becoming less ideal for *Coffea arabica.* This would suggest the potential for a feedback loop, in which robusta production and the associated deforestation lead even more farmers to convert to robusta in order to cope with changing environmental conditions.

If climate change is occurring in Kerala, it would not only be threatening cultivated coffee, but also a multitude of wild species. At least six species of wild coffee are known to occur in India.[25] According to a recent study there are now 124 known species of wild coffee, each with their own under-studied and potentially useful characteristics, such as drought or pest resistance, unique flavor profiles, or naturally decaffeinated beans.[26] Of these, an estimated 60% are threatened with extinction due mostly to climate change and habitat loss.[27]

The following analysis examines the local climate of Wayanad in recent decades to determine if any changes are occurring. Farmers interviewed during a field visit to Kerala assert that local conditions have become hotter and drier, especially during specific times of the year that are important to the life cycle of the coffee plant. The farmers of Wayanad have suggested an increasingly unpredictable monsoon season, a failure of the "blossom rains" in early spring, and a decrease in November showers. The following study was conducted to corroborate the personal experience of these farmers, and, in the event that trends are found, to determine if causal factors point to global-scale or local forcings.

Data Analysis

The district of Wayanad in the State of Kerala, India is a mountainous tropical region with altitudes ranging from 700 to 2100m above sea level, daily temperature minimums from 14˚ - 20˚ C, and daily temperature maximums from 25 – 32˚ C.[1] Kerala is the second largest coffee producing region in the country, responsible for 23% of India's total, and the district of Wayanad produces 90% of all the coffee grown in Kerala.[2] Wayanad is located in the Western Ghats mountain range, along the southwest coast of the Indian subcontinent, and receives a majority of its precipitation from the southwest monsoon period.[3] Thus it is an effective region in which to examine the potential effects of climate change, and alterations in the South Indian monsoon, on coffee production in India.



Map 1 shows a map of Kerala, with the study region of Wayanad in green.

In the following analysis, current trends in the local climatic conditions of Wayanad are examined and discussed as they pertain to coffee production. The roles of global warming and large-scale climate variability modes such as El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) as influential factors in Wayanad's local trends are investigated. Data suggests strong weather trends during the month of June, which may be significant for the production cycle of the coffee plant. Other factors examined include early Spring precipitation, which triggers the blossoming of the coffee flower, and November precipitation, which provides the moisture that sustains coffee plants during the immediately proceeding dry season.

Methods

Weather data were obtained from the Regional Agricultural Research Station for High Range Zone in Ambalavayal, Wayanad. The station is located at 974 meters above sea level, and is equipped with a class B meteorological observatory and automatic weather station. For this study, daily weather data from the years of 1984 – 2016 were examined. This included daily total precipitation, daily maximum temperature, and daily minimum temperature. ENSO and IOD values were retrieved from the United States' National Oceanic and Atmospheric Administration (NOAA) database. Indian Summer Monsoon Index values were retrieved from the Asia-Pacific Data-Research Center, at the University of Hawaii at Mānoa.

Data were examined in daily resolution, monthly resolution, and seasonal (4-month monsoon season/ 8-month dry season) resolution. All linear trends were calculated using the standard-least-squares approach, and all correlations were determined using the following equation:

$$Correl(X,Y) = \frac{\sum (x-\bar{x})(y-\bar{y})}{\sqrt{\sum (x-\bar{x})^2 \sum (y-\bar{y})^2}}$$

Where $\bar{x}$ and $\bar{y}$ are the sample means of array (x) and array (y), respectively.

Results

Over the 32-year study period, total precipitation in Wayanad during the monsoon season was found to be decreasing (slope = -6.75).

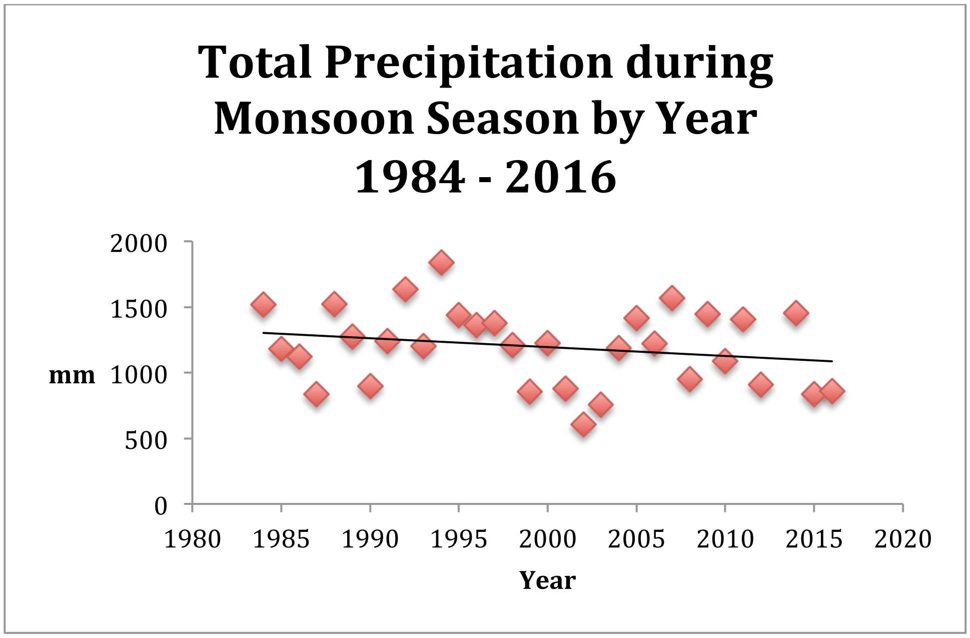


Figure 1 shows total sum of precipitation in millimeters during the period of June 01 to September 30, by year from 1984 – 2016. The standard-least-square best fit was found to be y = -6.754x + 14702.

Daily precipitation values in the top 90th percentile of total during the monsoon period were then calculated and isolated from the rest of the dataset. Annual sums from these high-value days were then calculated and found to also be decreasing over time.

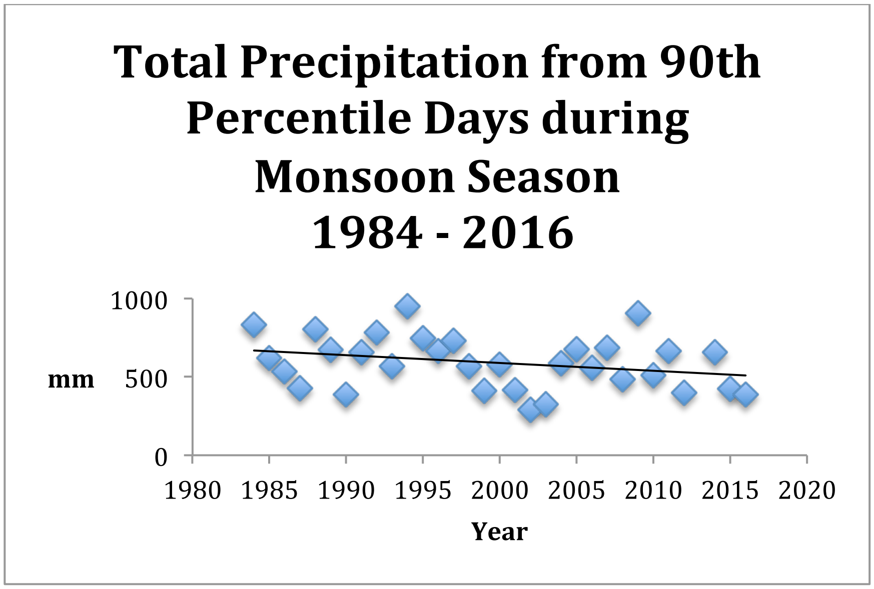


Figure 2 shows total sum of precipitation from only the 90th percentile of highest-value precipitation days for each year (1984 – 2016). Only data from the monsoon period (June-September) were used for these calculations. Annual sums from these days were found to be decreasing with a best fit of y = -4.975x + 10540.

These precipitation sum values from the 90th percentile days were then calculated as a percentage of the total precipitation that fell during the monsoon season from each year. A slight decreasing trend was found.

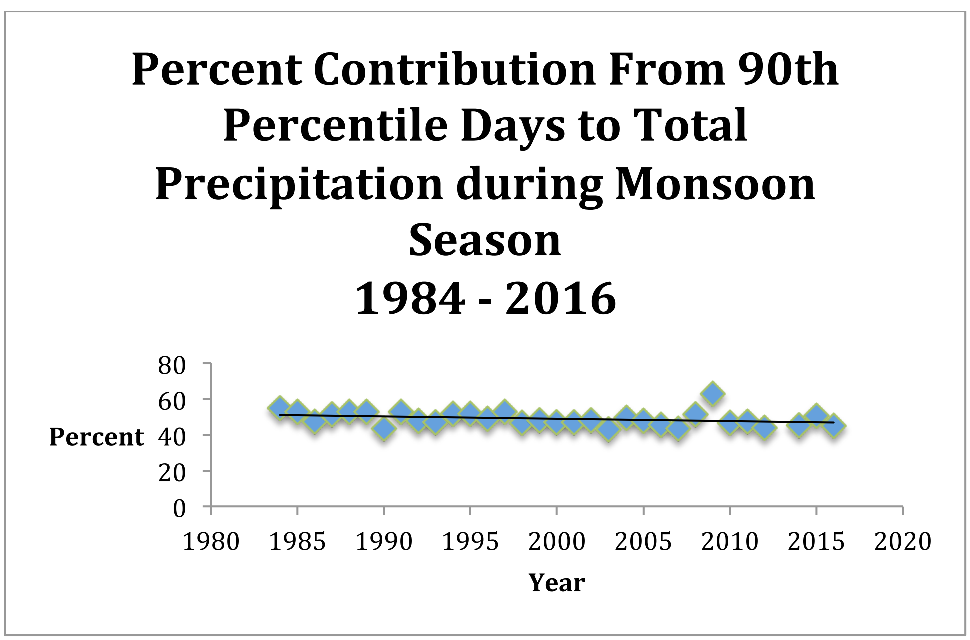


Figure 3 shows the sum amount of precipitation from the 90th percentile highest-value days, as a percentage of the total monsoon period precipitation. Y = -0.13x + 51.2

The dataset was then broken down into monthly increments, and the same calculations were repeated, with the following results:

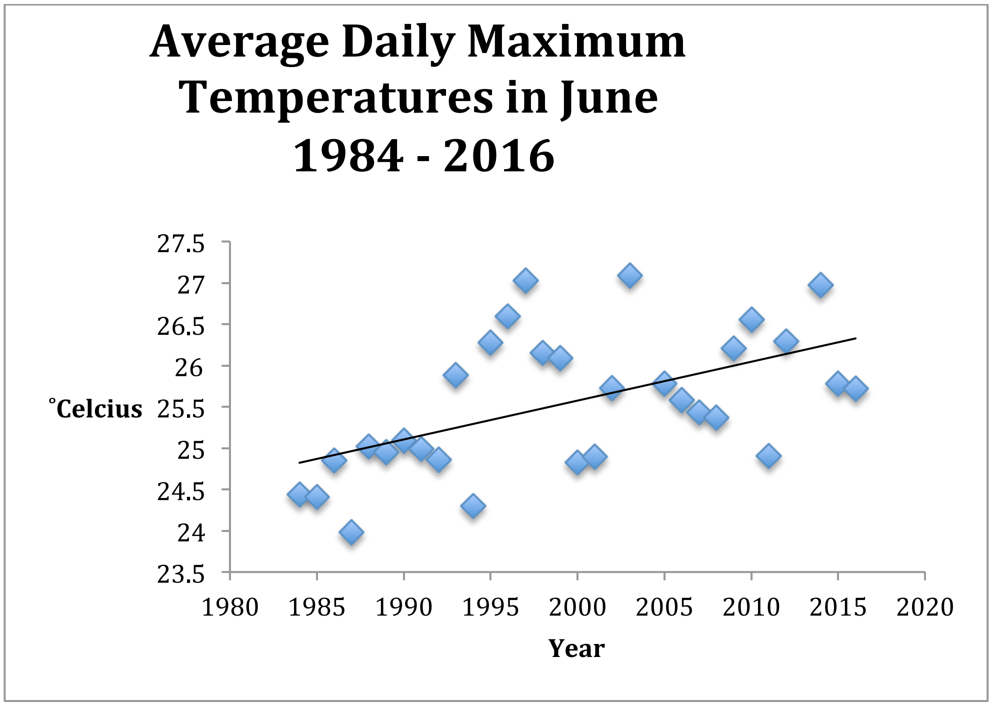


Figure 4 shows the average daily maximum temperature in June, by year from 1984 – 2016, with best fit line y = 0.05x – 68.485

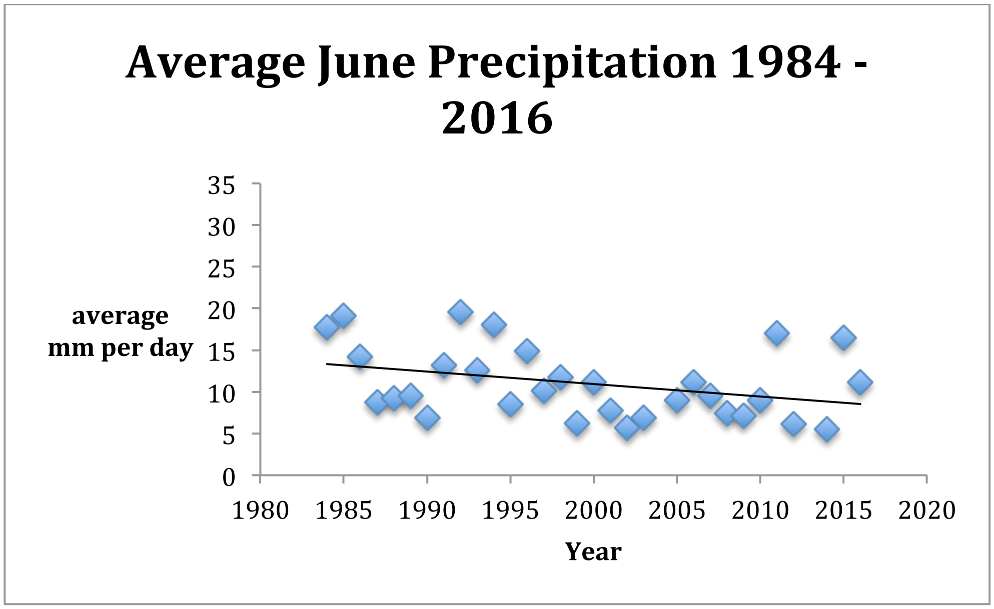


Figure 5 shows the average daily precipitation in June, by year from 1984 – 2016, with best fit line y = -0.15x +310.16

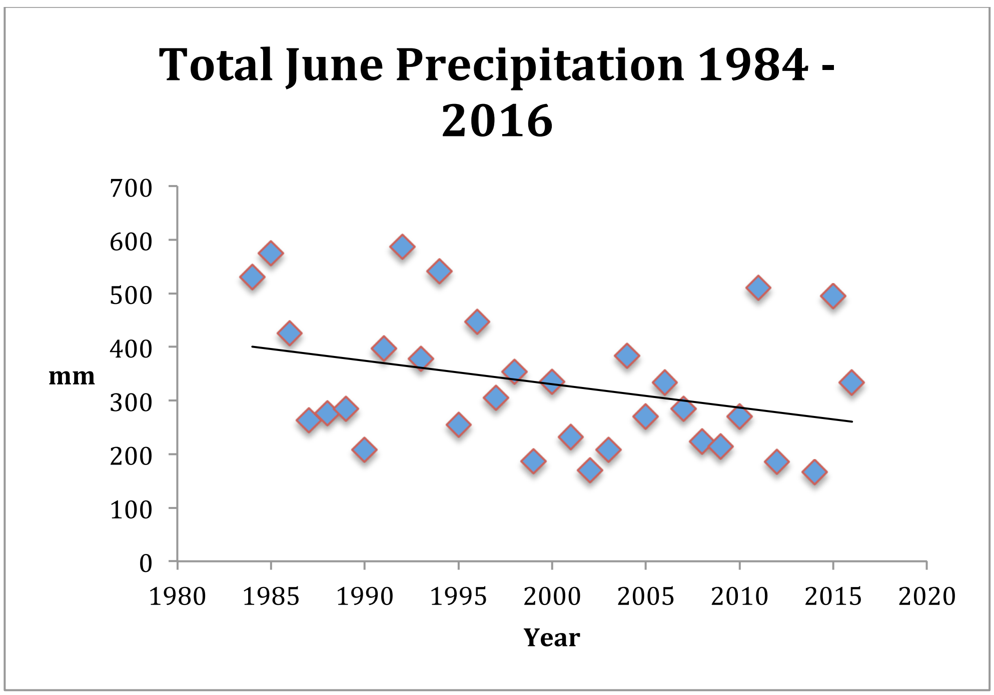


Figure 6 shows the sum total precipitation June, by year from 1984 – 2016, with best fit line y = -4.37x + 9075.3

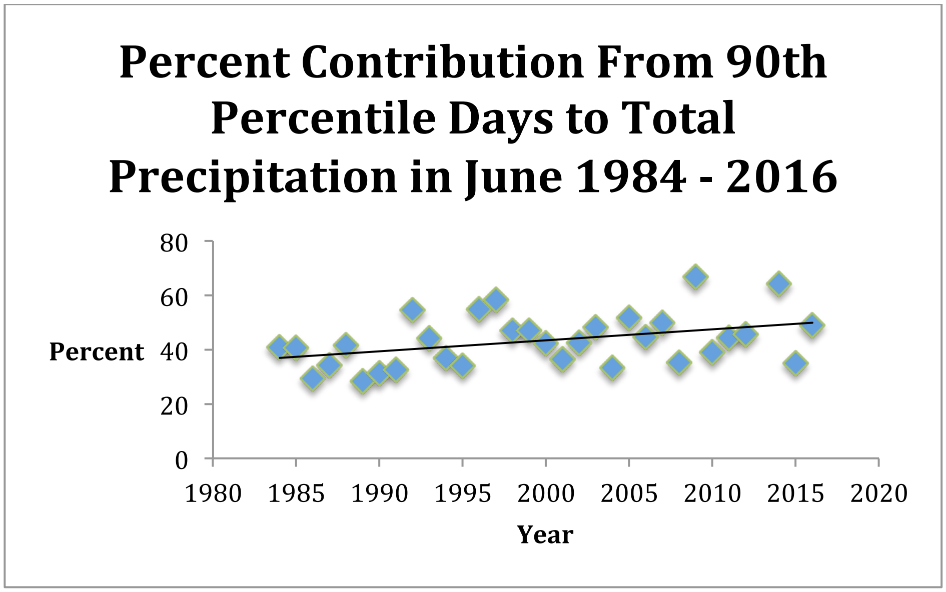


Figure 7 shows the sum amount of precipitation from the 90th percentile highest-value days in June, as a percentage of the total June precipitation, by year from 1984 – 2016. Best fit line Y = 0.4x – 765.66

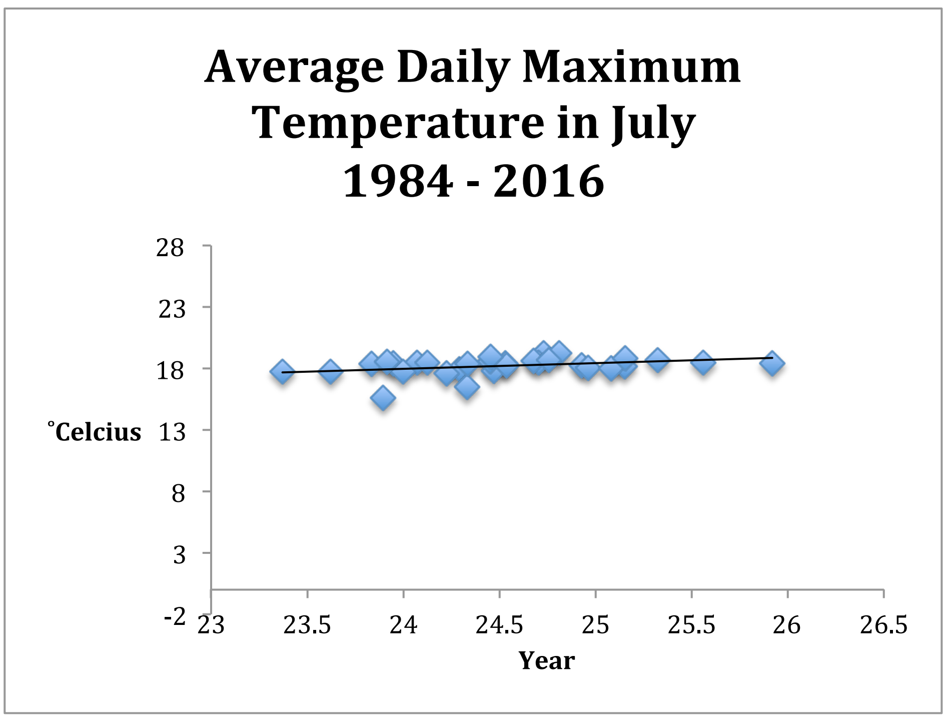


Figure 8 shows the average daily precipitation in July, by year from 1984 – 2016, with best fit line y = 0.46x + 6.85

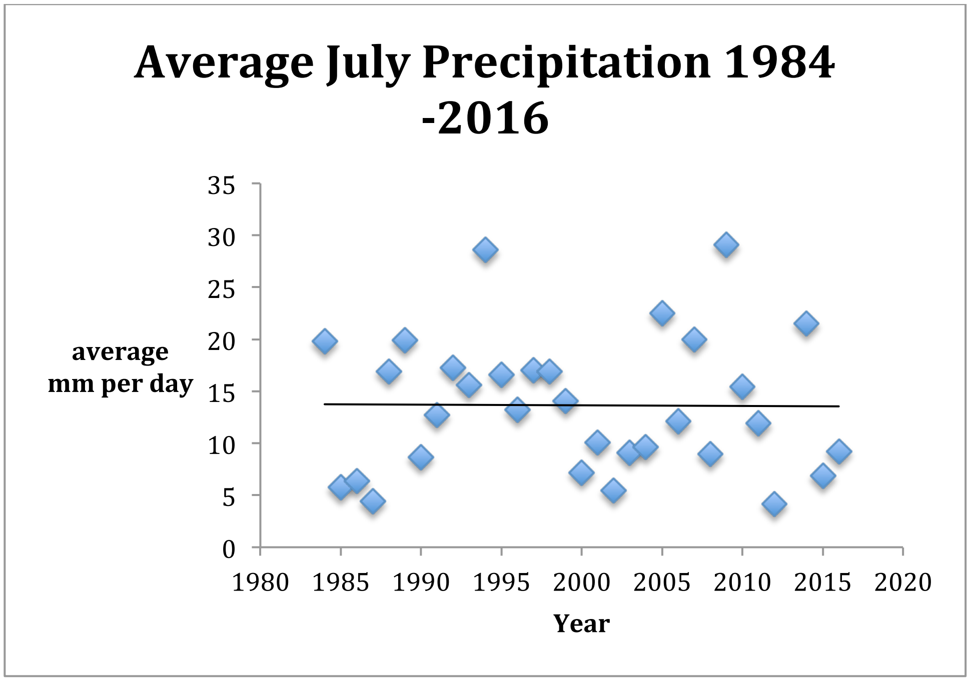


Figure 9 shows the average daily precipitation in July, by year from 1984 – 2016, with best fit line y = 26.23

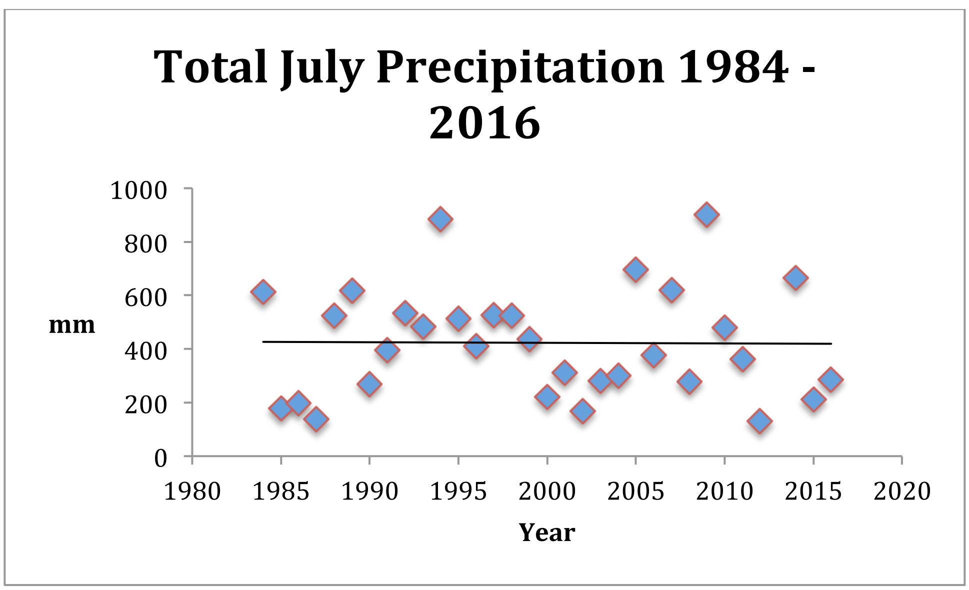


Figure 10 shows the sum total precipitation July, by year from 1984 – 2016, with best fit line y = -0.22x + 868.86

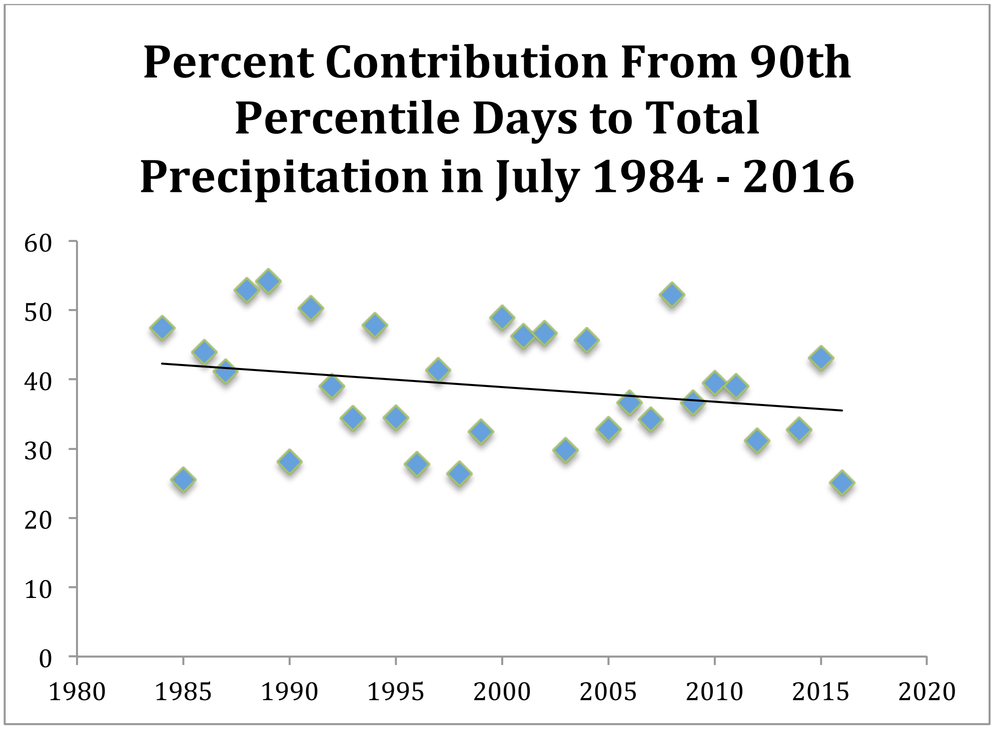


Figure 11 shows the sum amount of precipitation from the 90th percentile highest-value days in July, as a percentage of the total July precipitation, by year from 1984 – 2016. Best fit line Y = 0.37x + 774.84

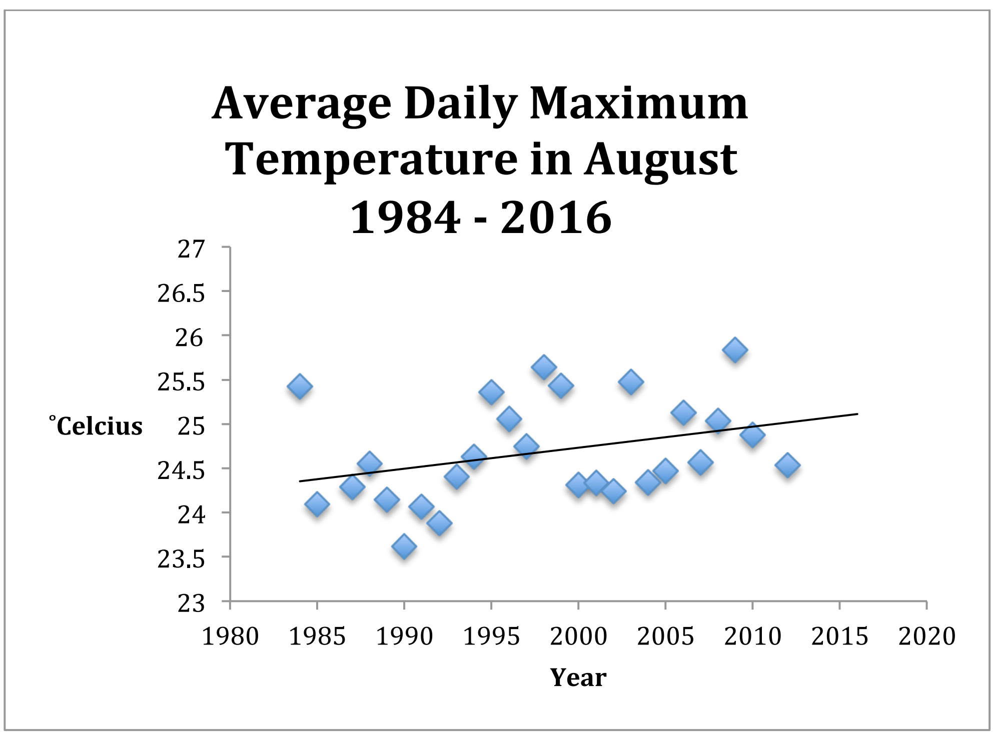


Figure 12 shows the average daily precipitation in August, by year from 1984 – 2016, with best fit line y = 0.02x +22.71

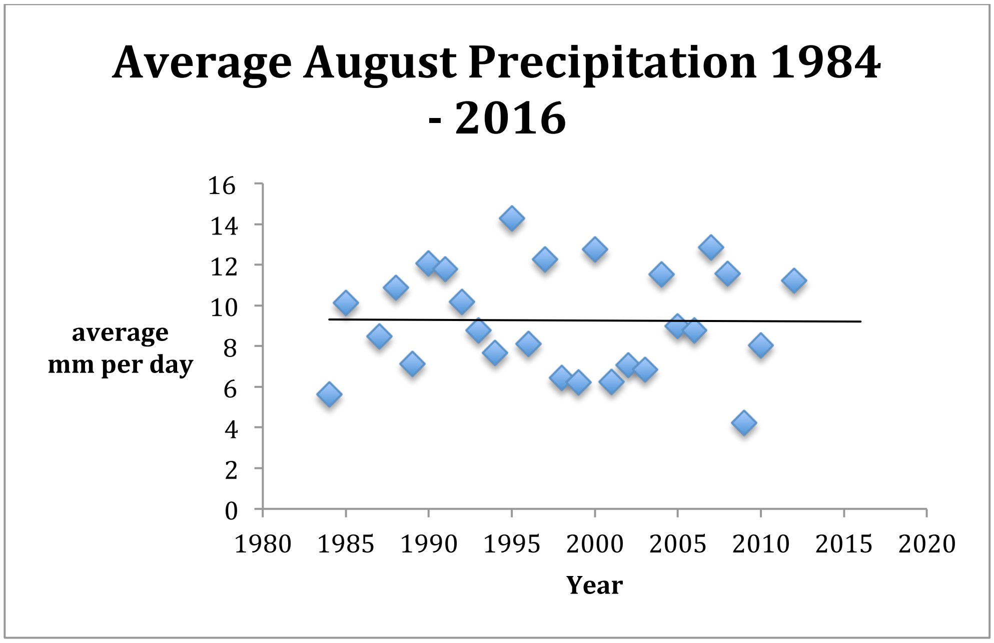


Figure 13 shows the average daily precipitation in August, by year from 1984 – 2016, with best fit line y = 15.69

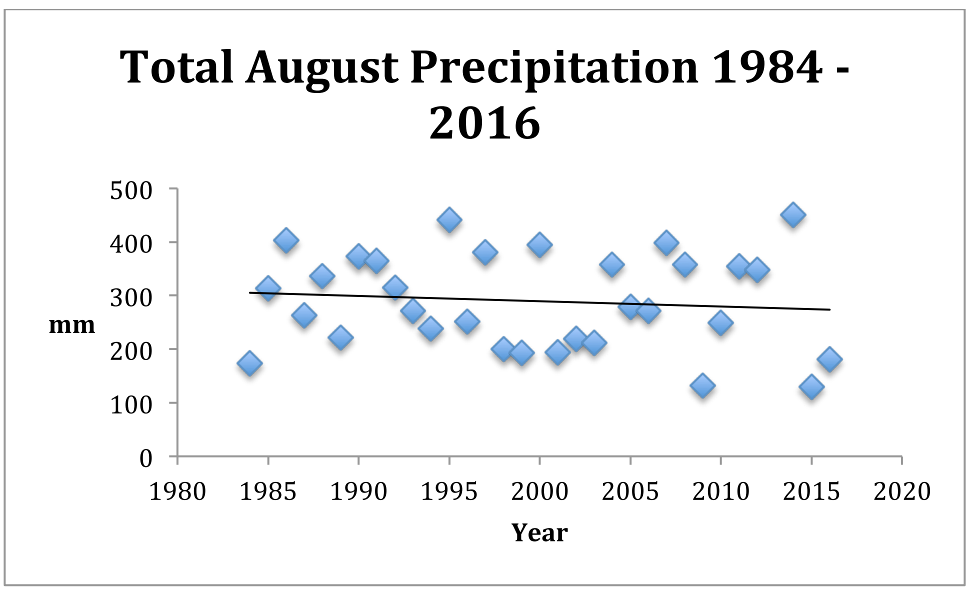


Figure 14 shows the sum total precipitation in August, by year from 1984 – 2016, with best fit line y = -0.98x + 2259.8

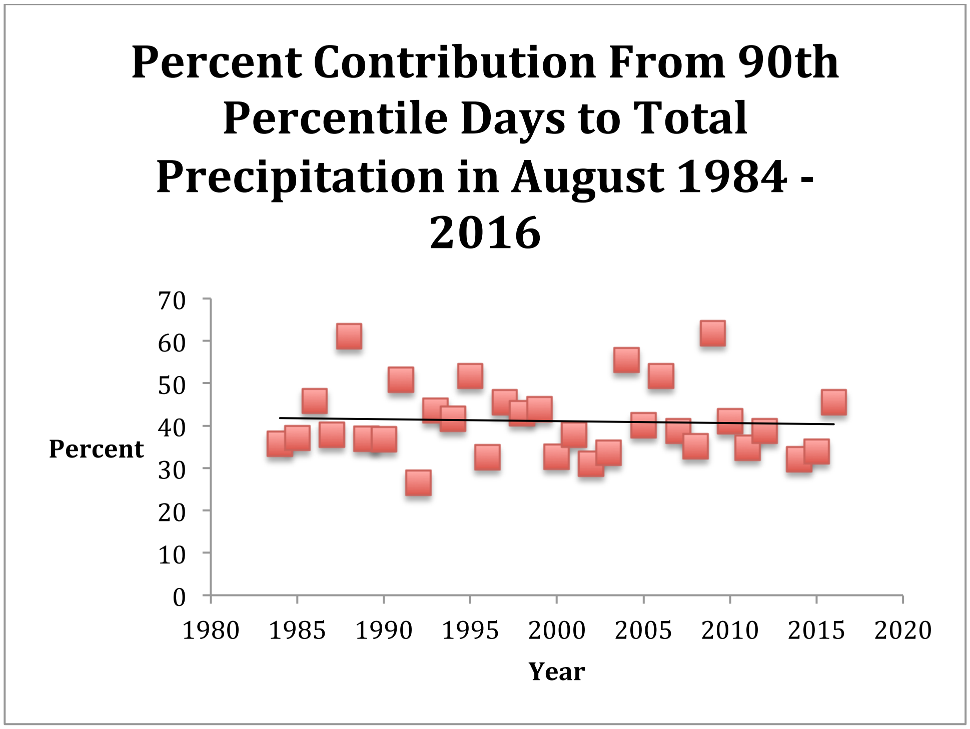


Figure 15 shows the sum amount of precipitation from the 90th percentile highest-value days in August, as a percentage of the total August precipitation, by year from 1984 – 2016. Best fit line Y = 0.04x – 131.26

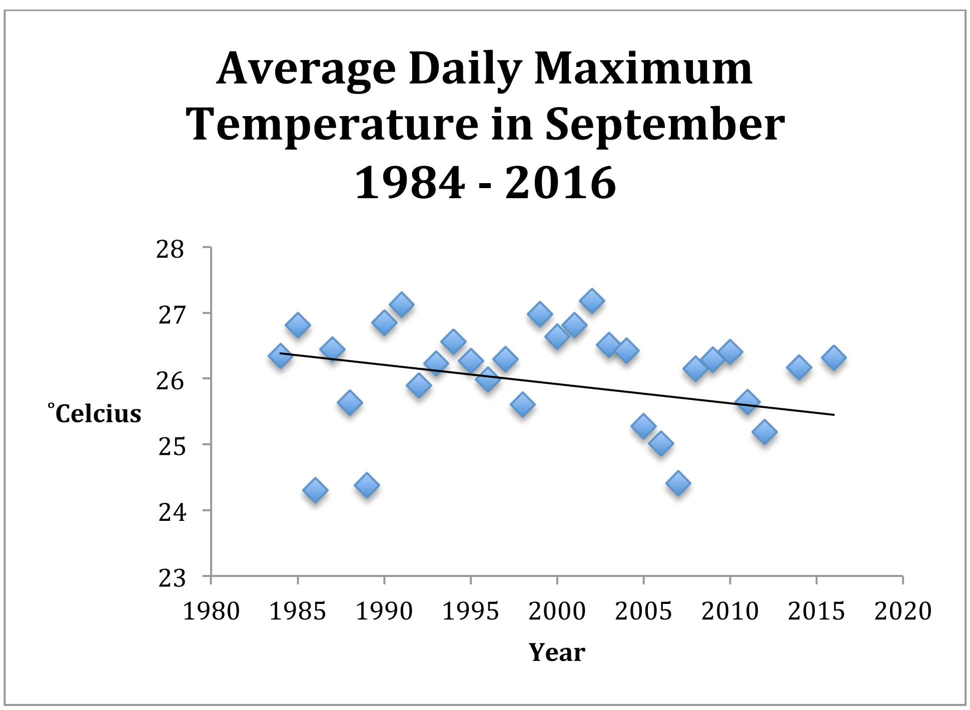


Figure 16 shows the average daily maximum temperature in September, by year from 1984 – 2016, with best fit line y = -0.03x + 84.31

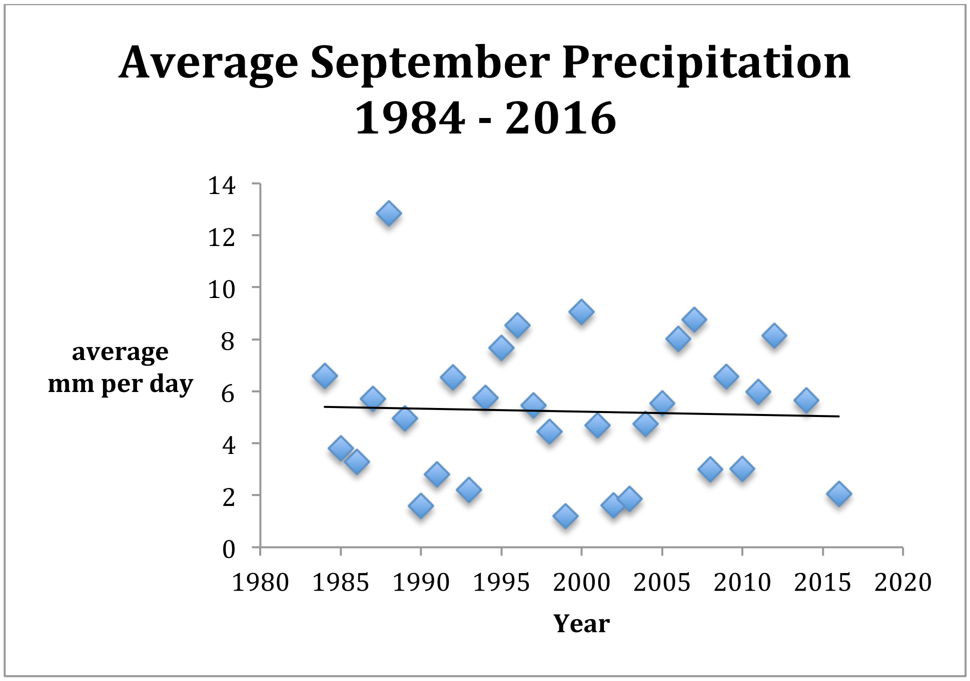


Figure 17 shows the average daily precipitation in September, by year from 1984 – 2016, with best fit line y = 28.09

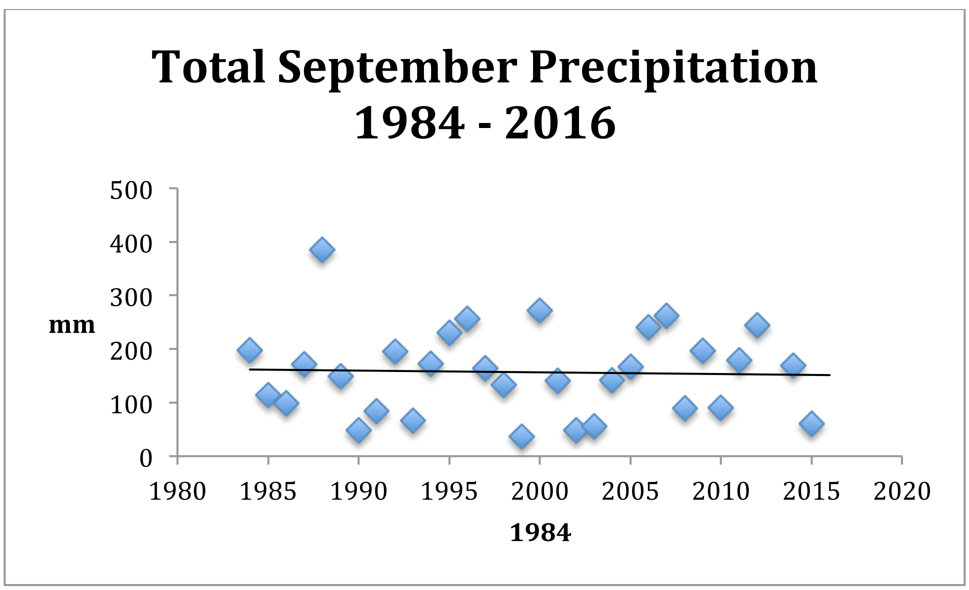


Figure 18 shows the sum total precipitation in September, by year from 1984 – 2016, with best fit line y = -0.32x + 802.96

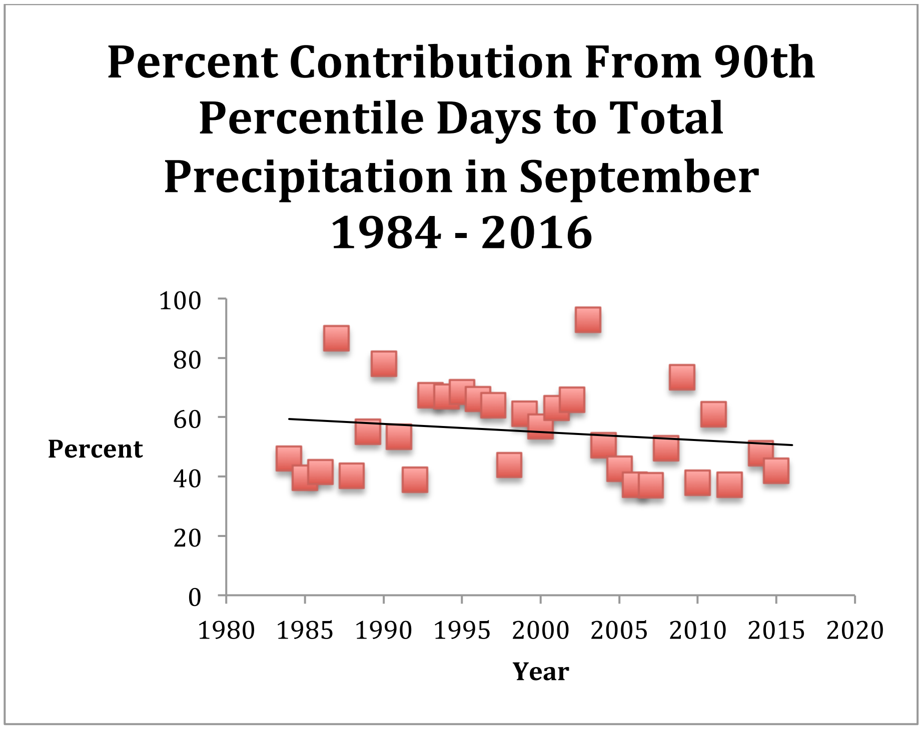


Figure 19 shows the sum amount of precipitation from the 90th percentile highest-value days in September, as a percentage of the total September precipitation, by year from 1984 – 2016. Best fit line Y = -0.27x – 604.13

To examine the timing of the monsoon onset, the first day in June with a precipitation value of greater than 25mm was isolated for each year. These days were plotted, with day of the month on the y axis, and year on the x axis.

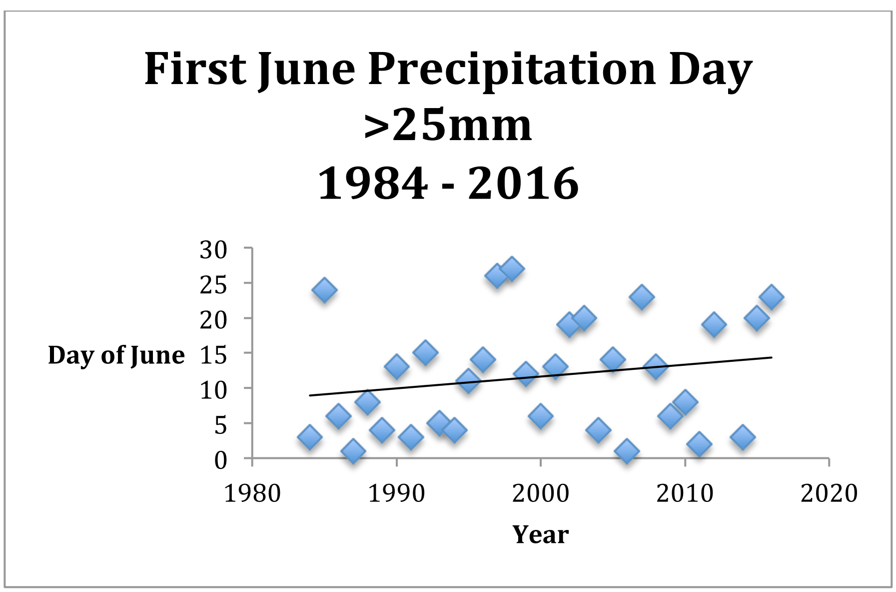


Figure 20 shows the first day of June with a recorded precipitation of greater than 25mm, by year from 1984 – 2016, with best fit line y = 0.17x – 326.45

To determine the influence of large-scale climate variability modes such as El Niño (ENSO) and Indian Ocean Dipole (IOD) on local temperature and precipitation in Wayanad, correlation coefficients were calculated. ENSO 3.4 index mean values from December, January and February were used to calculate El Niño correlations. For IOD correlations, the warmest monthly index value for each year was used. Indian Monsoon Index (IMI) mean values from June-September were used for those correlations.

June	Avg Daily Max Temp	Avg Daily Precipitation	Total Monthly Precipitation	Percent Precipitation from 90th Percentile Days
ENSO	0.118365461	0.053393245	0.059963022	-0.002879639
IOD	0.188042475	-0.108087571	-0.115135982	0.098433545
IMI	-0.207048405	0.187143873	0.19157681	-0.189804333

Figure 21 shows correlation coefficients between local Wayanad weather data and large-scale climate variables for the month of June using data from 1984 – 2016.

July	Avg Daily Max Temp	Avg Daily Precipitation	Total Monthly Precipitation	Percent Precipitation from 90th Percentile Days
ENSO	-0.122430236	0.116907262	0.118242683	-0.211250437
IOD	0.320425776	-0.035414226	-0.035578891	0.107136653
IMI	-0.540278092	0.190981042	0.191182932	0.025796405

Figure 22 shows correlation coefficients between local Wayanad weather data and large-scale climate variables for the month of July using data from 1984 – 2016. Significant correlations are highlighted.

August	Avg Daily Max Temp	Avg Daily Precipitation	Total Monthly Precipitation	Percent Precipitation from 90th Percentile Days
ENSO	0.023460284	-0.028611431	-0.043194475	0.10037774
IOD	0.240862763	0.04187338	0.01324621	0.167111108
IMI	**-0.373687395**	0.10997849	0.104591155	0.078142451

Figure 23 shows correlation coefficients between local Wayanad weather data and large-scale climate variables for the month of August using data from 1984 – 2016. Significant correlations are highlighted.

September	Avg Daily Max Temp	Avg Daily Precipitation	Total Monthly Precipitation	Percent Precipitation from 90th Percentile Days
ENSO	0.029342693	0.00210898	0.004881586	-0.017936913
IOD	0.030184772	0.095514669	0.096191164	0.033572118
IMI	-0.169569289	0.107888833	0.109852827	-0.139432068

Figure 24 shows correlation coefficients between local Wayanad weather data and large-scale climate variables for the month of September using data from 1984 – 2016.

Total precipitation from February and March, which is the blossom season for coffee in Wayanad, was then calculated by year. This was also calculated for the month of November.

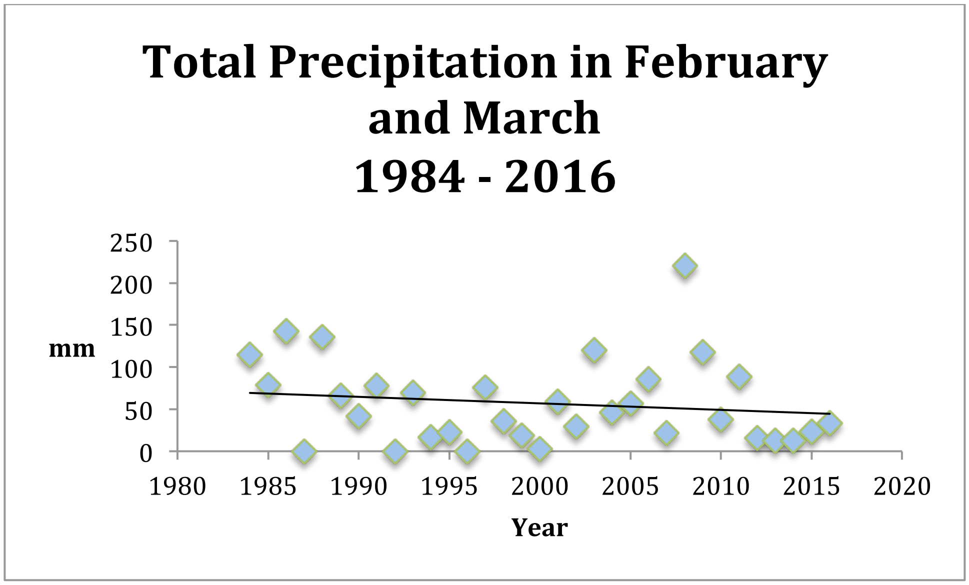


Figure 25 shows the sum total precipitation in February and March, by year from 1984 – 2016, with best fit line y = -0.78x + 1608.4

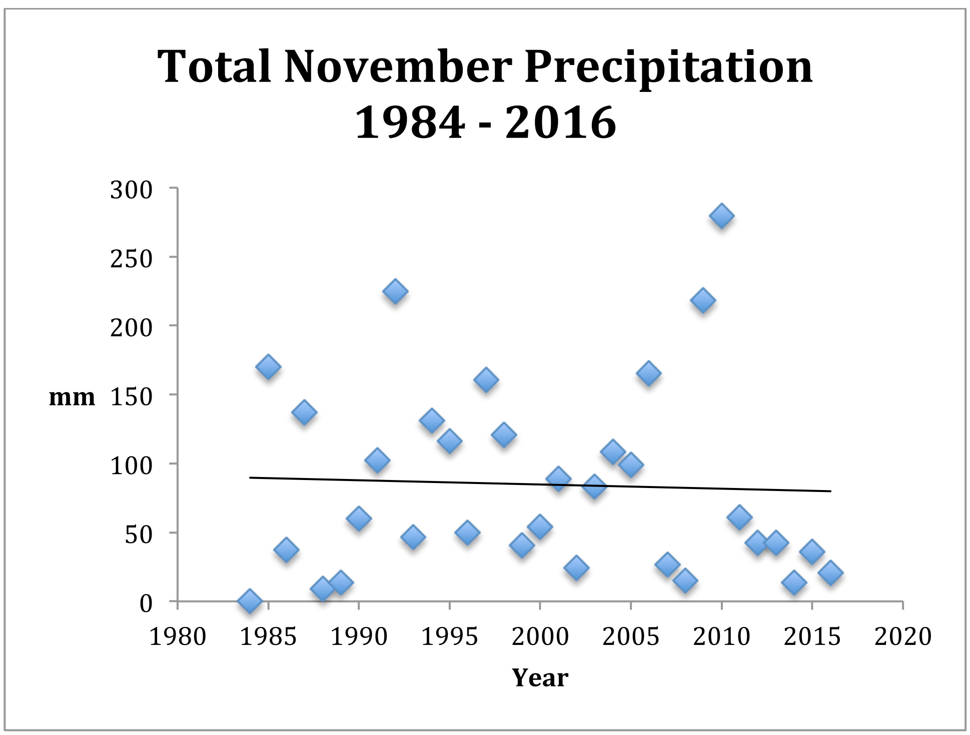


Figure 26 shows the sum total precipitation in November, by year from 1984 – 2016, with best fit line y = -0.31x + 696.13

Discussion

As seen above, daily maximum temperatures were found to be increasing over time in the months of June, July, and August. Daily maximum temperature was found to be decreasing over time by a negligible amount in September. This temperature increase could be attributed to the global-scale warming trend, but could also be due to other local factors, and further study would be necessary to determine this conclusively. Monthly precipitation values were found to be decreasing significantly in June, and no significant precipitation trends were found in other monsoon months. This implies a delayed onset of the monsoon season, which is consistent with other findings.[4] Another metric for monsoon onset, which is the first day of June with a recorded precipitation of over 25mm, also aligns with this finding. Total precipitation for the entirety of the monsoon period also displays a decreasing trend, suggesting an overall weakening of the monsoon that is also consistent with other findings for the region.[5] Thus it can be concluded that the local climate of Wayanad is experiencing changes in the monsoon that are consistent with the broader region.

While total amount of precipitation was found to be declining, the proportion of total precipitation that falls during the top 90th percentile days was found to be increasing. This trend was only found in the month of June. Though the exact nature of this trend remains inconclusive, the following two suggestions are proposed:

1) Factors responsible for the changes in weather patterns are disproportionately reducing the precipitation that falls on days with less rain.
2) Those factors are disproportionately increasing the precipitation that falls on days with more rain.

Further research is necessary to determine which of these is true. Regardless, this does imply that distribution of rainfall during monsoon onset is becoming less consistent, which could have logistical implications for agriculture in the region.

Because the correlations of Wayanad weather data to El Niño, Indian Ocean Dipole, and Indian Monsoon Index were not found to be significant, the results suggest that the weather trends in Wayanad are due to local variables, rather than broad-scale shifts in climate patterns.

Policy Review and Assessment

A review of the available literature reveals a multitude of policies to develop more efficient and sustainable agricultural practices, both in Kerala and more generally, which range in effectiveness. Based on existing literature, personal experience, and conversations with scientists and farmers, a brief analysis of these policies is provided below.

Practice-Based Recommendations

Polycultures, Intercropping and Shade Trees

While canopy trees can reduce annual yields of coffee and other crops, integrated multispecies systems are very likely to be more resilient to climate change in the near future. According to Prasanth one of the farmers interviewed during this study, while a full sun monoculture of robusta coffee in Kerala will yield approximately 900 kg / acre, a shade-grown system will yield only 700 kg / acre. However, intercropping with canopy trees provides cooler air temperatures, which is likely to protect understory crops such as coffee from future heat waves. Shade trees have been shown to decrease leaf temperature of coffee plants by up to 4°C in sub-optimally hot conditions (Vaast et al 2004). In addition, shade creates cooler soil temperatures, which increases microbial and mycorrhizal activity. This in turn increases uptake of nutrients in crop plants, which promotes better plant health and can increase yields (Montgomery 2017).

A robust canopy layer has also been shown to decrease both soil evaporation and crop transpiration, which can substantially increase soil moisture available for crops to use during photosynthesis (Lin 2010). Canopy layers also reduce precipitation velocity, which reduces erosion and crop damage (Brandt 1998). If adopted at a large enough scale, reinstating a living canopy layer across Kerala is likely to be the state's single most effective strategy for agricultural resilience in the face of climate change.

Shade trees can also provide supplemental income to buffer or even surpass coffee yield losses, if commodity-producing trees are used. Shade trees well suited for coffee agroforestry in Kerala include rubber (*Ficus elastica*), mango (*Mangifera indica*), areca nut (*Areca catechu*), teak (*Tectona grandis*), silver oak (*Gravillea robusta*), and jackfruit (*Artocarpus heterophyllus*). It has been recently suggested that mango trees are particularly well suited for growth alongside coffee due to their tendency to draw water from the deeper subsoil level, thereby reducing competition for water, as coffee draws the majority of its water from the topsoil layer (Hombegowda et al 2019). Studies indicate that optimal shade levels for coffee production are approximately 20-40%, however this can vary based on local ecological and economic conditions (Vaast et al 2004). If species are selected carefully based on local conditions, shade trees can provide substantial economic synergies to coffee agroforestry systems.

In conjunction with a canopy layer, additional crop species can be utilized to increase farm productivity-per-acre. Black pepper (*Piper nigrum*) can be planted in tandem with shade trees. The pepper plant, which is a vine, can be made to grow using the shade trees for support. Pepper also has a different harvest season than coffee, which is a useful synergy from a logistic perspective. An understory of turmeric, ginger, and other spices can be planted as well, or alternatively an understory of nitrogen-fixing cover crops to increase soil fertility.

Building Soil Health

Building soil health, which for these purposes can be translated to increasing soil carbon content, water holding capacity, and microbial richness, can significantly buffer a farmer's vulnerability to economic and environmental uncertainties. An increasing number of studies suggest that the single best metric for long-term soil fertility is carbon content. While fertilization with synthetic nitrogen, phosphorous and potassium compounds can lead to short-term yield boosts, building organic content in soil vastly improves long-term yields by increasing water retention, reducing erosion, and building healthy microbial ecosystems. (Montgomery 2017). A review paper encompassing a multitude of crop species in agricultural systems across the globe concluded that soils with higher carbon content consistently produced higher yields, especially in dry years (Lal 2005).

Soil carbon content can be increased by mulching, composting, or cover cropping. All of these practices require little to no technology and can be implemented at very low cost to the farmer. Organic matter can be added to soils in the form of manure, crop residues, or waste pulp from coffee processing. In Kerala, these products are often dried and burned for use as cooking fuel. However, some products, most notably coffee pulp, often goes to waste. Art Donnelly, founder of the Estufa Finca project, has invented a low-cost cooking stove that uses a dual-chambered, oxygen-restricted combustion system to burn organic coffee waste products in a way that produces both a clean-burning cooking flame and carbon-rich charcoal, or biochar. This charcoal can be applied to fields directly, and a number of studies find this application to boost both microbial activity and crop yields (Biederman 2013). The biochar can also be fermented to produce a microbe-rich fertilizer. This process is also low-cost and low-tech. A 2017 account of a Costa Rican farmer named Echeverría describes the process:

"This low-tech microbial inoculant employs a sourdough-like starter to brew up a biofertilizer rich in mycorrhyzal fungi. To get it going, Echeverría collects a bag full of organic matter (humus) from the forest floor, making sure that it contains white fungal hyphae. Next, she removes all the big leaves and mixes it up with rice bran and molasses. She then covers it with a plastic bag in 60-liter, screw-top containers and lets it ferment for a month and a half." (Montgomery 2017).

An account of Gabriel Umaña, an agent for the Costa Rica Ministry of Agriculture, attests that application of fermented biochar even "synchronizes maturity among coffee bushes. This helps farmers with a major logistical problem, as coffee beans must be sold when ripe." (Montgomery 2017). Notably, biochar relies on the synthesis of carbon-based plant matter via photosynthesis, and the process of incomplete combustion returns a portion of this carbon to the soil. As such, it is the only known form of energy production that is net carbon negative.

In addition to building soil carbon content, employing no-till farming practices, robust mulching or cover cropping, and diverse crop rotations are essential to promoting soil health. Frequent tillage has been shown to result in decreased soil carbon and loss of fertility (Lal 1994). Covering the soil surface with mulch, cover crops, or other organic residues has been proven to conserve soil moisture and reduce erosion (Van Doren and Allmaras 1978, Unger et al 1988). Surface mulch from crop residues has been shown to affect crop yields due to its variety of physical, chemical, and biological impacts on soil characteristics (Kumar & Goh 2000). Long-term studies have shown that agricultural practices that combine crop rotations, consistent surface residue, and reduced tillage result in soils with higher levels of carbon and nitrogen (Havlin et al 1990). Crop rotation is also associated with increased microbial diversity in soils, which in turn reduces risk of pest outbreaks due to natural biological control mechanisms (Leake 2003).

Integrated Pest Management

Utilizing a variety of pest control strategies, although sometimes requiring more effort, is more effective in the long run than relying solely on chemical pesticides. Studies show that relying on heavy usage of a single pesticide leads to chemical resistance in insects and is an ineffective long-term strategy for pest control (Georghiou 1972). Pest management practices should be diverse and integrated. For coffee farmers, these practices can include the following:

- **Natural Chemical Control** An effective, naturally derived chemical pesticide made from tea of the "neem leaf" (*Azadirachta indica*) is cheaper than manufactured pesticides and can be made at home. The tea can be sprayed on the leaves of coffee trees and other plants and is not harmful to humans. (Schmutterer 1990).

- **Light Traps** A study by MSSRF has shown that a significant number of insect pest species are active from 7pm – 9pm. Burning oil-lamp insect traps during this timeframe disproportionally attracts pests over other insect species. As a majority of beneficial insects are active later in the night, this temporally sensitive employment of light traps is recommended as a cheap and effective strategy to eliminate insect pests.
- **Border Crops** Nectar-producing plants can be planted along the borders of farms to attract pests away from cash crops, and provide habitat for natural pest predators. Border plants can include both plants that are not utilized for consumption or supplemental food crops. Studies show that there are many plants effective for this use, but some examples include sunflowers (*Helianthus annuus*), eggplants (*Solanum melongena*), chili peppers (*Capsicum annuum*), and Indian hemp (*Crotalaria juncea*) (Gurr et al 2016).

Policy Recommendations

Increased Canopy Tree Incentives Through MSSRF, the State of Kerala's Ministry of Agriculture already provides stipends to farmers to keep native species of shade trees on their properties. In addition, a separate Tree Stipend Program has recently been developed that engages the private sector. In this program, the government sponsors banks to give financial support to farmers who plant trees. In exchange for the initial investment to plant the trees, the banks then own the assets associated with the value of the tree on the farmer's property, much like a lien. However, these programs should be provided much more funding. According to Prasanth, a typical stipend to keep a rosewood tree (*Dalbergia sissoo*) is approximately 700 rupees per year (~$10 USD), whereas the profits from cutting the tree and harvesting its timber is closer to 70,000 rupees (~$1,000 USD). As such, the tree stipends should be increased by at least two orders of magnitude in order to be a policy that is effective at retaining participants.

Soil Carbon Incentives In lieu of providing frivolous crop insurance payouts that subsidize bad farming practices, it is recommended to incentivize practices that build topsoil and increase soil carbon content. During the course of this study, soil carbon content was found to be the single most applicable metric correlated with sustainable and resilient farming practices. Establishing simple incentives based on a single metric reduces organizational costs for the governing body, while simultaneously encouraging a diverse array of carbon-sequestering farming practices that work synergistically to build economic and climate resilient agriculture. Measuring soil carbon content is low-effort and low-cost, and the monitoring efforts that would be required to award financial incentives responsibly are likely to be fairly cost-effective relative to other similar incentive efforts. This policy could be achieved through subsidies, stipends, or other incentive measures.

Education and Outreach In order for any of these policies to be effective, awareness and education must be brought directly to the farmers. Studies indicate that one of the most effective methods to encourage the adoption of new farming practices is the establishment of full-scale demonstration farms within the agricultural communities (Newton 2001). MSSRF's Botanical Garden presents a fortuitous opportunity in Kerala, as it is already established, staffed, and well known within the community. This would be an excellent location to establish a pilot program for carbon farming workshops, in which information and hands-on lessons about regenerating topsoil and soil carbon can be provided. If successful, these demonstration farms could be replicated in other communities.

Recommendations from the Farmers

In interviews with farmers, one of the topics discussed was government policy. The question I posed to farmers was the following: "What kinds of new policies would be most helpful to support coffee farmers in Kerala?" Of the 13 farmers I spoke with, they offered the following four suggestions:

- **Better Access to Weather Information** 11 of the 13 farmers interviewed reported relying on Accuweather for their weather information, and the remaining 2 cited local radio as their primary source of weather information. None of the farmers interviewed reported having access to high-quality national weather data. In addition, weather stations in rural farming regions of India are consistently sparse compared to urban centers. National weather services should be expanded in agriculturally active regions. One farmer by the name of Mr. Devakeran provided a concise analysis of the politics regarding funding for weather information in India in the following way: "They put the weather stations in the city so the Minister can decide if he needs an umbrella. Here we depend on weather information for our entire livelihood, and yet we are ignored."
- **Guaranteed Minimum Commodity Prices** Farmers want protection against the extreme price volatility of the commodity market. In fact, the implementation of guaranteed floor prices for coffee was common practice in India from the 1930s all the way until the 1990s when economic liberalization occurred (Lee 2007). A reinstatement of the Coffee Board of India would protect farmers against price volatility and would enable them to budget themselves responsibly on an annual basis. However, the Coffee Board's historical practice of pooling all coffee within a region for export reduced incentives for individual farmers to improve the quality of their harvests. To ameliorate this, a scaled floor price could be implemented based on bean quality. The Specialty Coffee Association of America has recently

developed a framework for quantifying bean quality on a 100-point system (Mutua 2000). This framework could be adopted in order to implement such a scaled floor pricing system.

- **Crop Insurance** Farmers want government-guaranteed crop insurance to protect against crop failures. However, studies show that crop insurance can lead to moral hazard and negligent farming practices, especially in years with unfavorable growing conditions (Coble et al 1997). As conditions for growing coffee are predicted to worsen consistently in the foreseeable future, crop insurance is likely to suppress innovation and adaptation. While insurance against extreme weather events such as the devastating 2018 flood is essential to safeguard against total economic loss, overly lenient or accessible insurance policies are not recommended in this analysis. Other forms of government support that incentivize improved farming practices are discussed below.
- **Irrigation Infrastructure** While artificial irrigation would certainly protect farmers against droughts and unpredictable weather patterns, it is likely that widespread construction of irrigation infrastructure in Kerala would be prohibitively expensive. While further analysis would be needed to determine this conclusively, mountainous topography, small, widely dispersed landholdings, and lack of existing supportive infrastructure such as roads make the feasibility of irrigation unlikely.

Awareness and Outreach

In an effort to increase consumer awareness of the current state of the coffee commodity market and its effects on smallholder producers, an amended version of the Introduction section of this report is being published and distributed among coffee shops in the San Diego area, along with a link to the full report. In addition to the article, a list of San Diego coffee shops that implement ethical coffee purchasing practices is included, to promote awareness of socially responsible coffee companies. The publication encourages consumers to support importers with business models that don't undermine the livelihoods of producers and the ecosystems that sustain them. Engaging consumers in a way that changes their preferences is one of the most effective ways to enact change in market economies.[1]

In addition to consumer outreach for the sake of increasing awareness, a fundraising effort was established to support the M. S. Swaminathan Research Fund and the work they are doing to improve conditions for farmers in Kerala. During the month of July 2019, a portion of the proceeds from merchandise sold at Bird Rock Coffee Roasters will go to MSSRF. This partnership represents an easily replicable business model for any coffee business that wants to connect consumers with producers in a way that builds resilience and ethical practices into their supply chain.

Conclusions

Kerala faces an economic situation that encourages farmers to adopt practices that exacerbate climate change and biodiversity loss, erodes coffee quality, and undermines farmer's livelihoods. In the biodiversity hotspot of Wayanad, Kerala, weather is getting hotter and drier, particularly during months when precipitation is vital to the life cycle of the coffee plant. These trends compound the existing threats faced by farmers and biodiversity in the region. Personal experience of farmers in Wayanad was corroborated by quantitative analysis. Researchers studying agricultural systems should engage with local constituents to guide research efforts, particularly in regions where tribes have yet to be disenfranchised and ancient knowledge is still intact.

Reforestation, reinstatement of traditional intercropping methods, and regeneration of healthy soils are likely to be the most effective strategies for both climate and economic resilience. Price stabilizing mechanisms such as a guaranteed floor price should be reinstated, as they were in the past, to protect farmers against multinational vested interests. Policies that incentivize carbon sequestration and reforestation should be implemented in order to mitigate and adapt to climate change, and to provide better livelihoods for the people that grow crop commodities. Consumers should be engaged and educated on these issues in order to shift market forces towards business practices that support these efforts.

Readers of all affiliations should consider the global impacts of their daily choices as consumers, strive towards lifestyles that eliminate frivolous use of resources and promote ethical economies, and participate in the world in a responsible way for the sake of all life on Earth, including present and future generations.

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