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Impact of Climate Change on the Production of *Coffea arabica* at Mt. Kilimanjaro, Tanzania

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Abstract: Adapting coffee production to climate change is a significant challenge requiring a detailed understanding of local climatic change patterns and the consequences, both real and perceived, for coffee production. To this end, we examined changes in precipitation at Mt. Kilimanjaro over the last two decades and conducted twelve focus group discussions to obtain farmers' perceptions on climate change, the impact of extreme weather events on coffee production and the potential of shade trees as an adaptation strategy. Despite an increase in total annual precipitation, farmers are still confronted with droughts due to a shift in seasons. We found a delayed onset of the main rainy season and showed that a positive Indian Ocean Dipole contributes to the increase in precipitation during the short rainy season. Farmers clearly described the impacts of drought or excess rainfall on coffee production during flowering, maturation, and harvest. Thus, adaptation strategies need to be tailored such that specific coffee development stages are buffered against the effects of droughts, shorter wet seasons, and less frequent but heavier rainfall events. To develop the potential of shade trees as an effective adaptation strategy, optimum shade density, specific tree species, and management practices need to be identified.

Keywords: climate change; East Africa; *Coffea arabica*; shade trees; farmers' perceptions

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1. Introduction

Globally, climate change poses a serious challenge to crop production with agriculture-dependent countries, like Tanzania, hit especially hard. East Africa will be increasingly affected by climate change in the coming decades, with temperatures already increasing and predicted to rise further [1–3]. Mean temperatures in Tanzania's *Coffea arabica* growing regions increased by 1.42 °C between 1960 and 2010 and are projected to rise by a further 2 °C by 2050 [2,4]. The effect on rainfall is more difficult to predict [5]. Warmer air means quicker water evaporation from surfaces, causing dry spells or droughts [6]. However, warmer air can hold more humidity, which can cause heavier rainfall events, leading to flooding [7]. Farmers in East Africa will likely have to adapt to both extremes [7–10]. Another challenge is the increasing fluctuation and intensity of the El Niño–Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) due to climate change, leading to a stronger variation of climate patterns and a shift in seasons that farmers will need to adapt to [11–13].

Coffee is an especially important agricultural commodity for Tanzania. It generates about 100 million USD annually in export earnings and supports the livelihoods of about 2.4 million individuals from mostly smallholder farming households [14]. *Coffea arabica* as well as *Coffea canephora* var. Robusta are produced in Tanzania [14]. *Coffea arabica* is mainly cultivated in the northern highland region (including Mt. Kilimanjaro, Mt. Meru, and Ngorongoro Crater highlands) and in the southern highland regions (Mbinga and Mbeya) [2,14].

Coffea arabica evolved as an understory species in the forests of the Ethiopian highlands and as a result is a very climate sensitive plant [15]. Research has shown that yields are especially affected by minimum temperatures [2]. It is predicted that in Tanzania every 1 °C increase in minimum temperature will result in annual yield losses of nearly 140 kg/ha [2]. *Coffea arabica* requires average annual temperatures between 18 °C and 21 °C, with optimal mean nocturnal temperatures of 15 °C [15,16]. The optimum annual rainfall range is 1200–1800 mm [17]. Flowering of *Coffea arabica* is triggered by rains after a dry period [18–20]. At. Mt. Kilimanjaro, this can start in August and September, with the main period being between October and December. Depending on the elevation, flowering can last until March. Some fruit shedding takes place during the first three months after flowering [21]. After the fruit expansion stage, however, the coffee plant is committed to filling all the beans [22]. This is due to the evolution of *Coffea arabica* under shaded conditions, where it originally did not set a lot of fruits and therefore did not develop adequate mechanisms for fruit shedding [22]. Harvest at Mt. Kilimanjaro takes place between June and November, with peaks in August and September.

Besides the potential impact on yields, climate change further threatens coffee quality as warmer temperatures speed up maturation, which could lead to smaller sized, lighter, and less dense beans [22,23]. The severity of pest attack and disease spread is likely to increase with advancing climate change, a significant challenge for coffee production [24,25]. This will render areas currently under coffee cultivation unsuitable for coffee production, pushing production into higher elevations [2,26]. A possible mitigation strategy could be agroforestry, as shade trees might buffer rising temperatures and weather extremes. Agroforestry systems show potential to mitigate temperature and humidity extremes as well as variability in soil moisture [27,28].

The aims of the study were (1) to identify the extent of climate change and extreme weather events farmers at Mt. Kilimanjaro experienced in the last two decades, (2) to relate changes in weather to ENSO and IOD extremes to determine possible effects on future climate, (3) to better understand the impacts of climate change on coffee production in the region, by surveying farmers' perceptions of climate change and the impacts of extreme weather events on coffee production, and (4) to understand farmers' perceptions of potential climate change mitigating effects of shade trees.

2. Materials and Methods

2.1. Study Area

This study focuses on the *Coffea arabica* growing area on the southern slope of Mt. Kilimanjaro (Tanzania) where coffee is cultivated in commercial plantations and by smallholder farmers between 1000 and 1800 m asl [29]. The smallholder farming systems are very diverse, including a variety of fruit trees, banana plants, and other food crops besides shade trees and coffee plants [29,30].

2.2. Historic Climate Data

We obtained monthly precipitation records from 2001 to 2019 from three coffee plantations covering twelve coffee growing areas on the southern slope of Mt. Kilimanjaro (Figure 1). We examined the total annual rainfall per year for each area to identify any significant increases or decreases in precipitation. We further calculated average annual precipitation and compared this with the overall average precipitation to identify extremely wet and dry years.

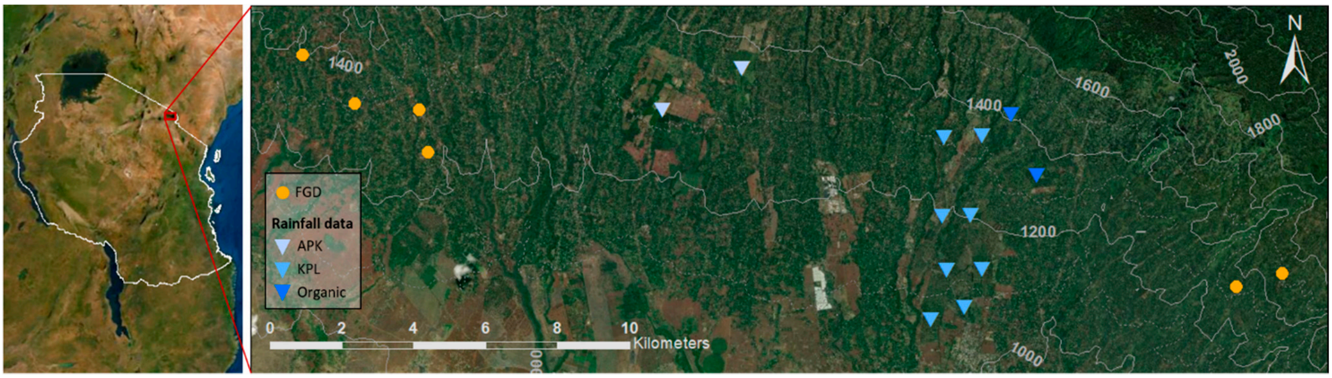

Figure 1. Location of the study area within Tanzania, locations of the focus group discussions (FGD) and the areas for which we obtained historical climate data. The three coffee plantations are African Plantation Kilimanjaro Ltd., Moshi, Tanzania (APK), Kilimanjaro Plantation Ltd., Moshi, Tanzania (KPL), and Blue Mountain Coffee Farms Ltd., Moshi, Tanzania (Organic).

We calculated the percentage of months per year with high or low rainfall by considering the areas separately and marking the 25% highest values of all recordings for each area as wet months and the lowest 25% as dry. This approach helps to account for natural variation in rainfall amount between areas. Years were classified as wet if more than 30% of the months of all areas were marked as wet and classified as dry if more than 30% of the months were marked as dry.

We identified a shift in seasons by two different methods. First, we compared the average monthly precipitation within the timeframes 2001–2009 and 2010–2019. Significant differences were tested with t-tests. This gives a visual representation of potential shifts in seasons. Secondly, we looked at correlations between years and precipitation per month for all years. This shows if there is a trend of increasing or decreasing precipitation for the different months over the whole period.

2.3. Comparison with El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) Phenomena

Monthly sea-surface temperature anomalies from 2001 to 2019 were obtained from the World Meteorological Organization [31]. For ENSO the zone NINO3.4 (5° N–5° S; 120–170° W) was used, as it is highly representative, especially for effects on precipitation patterns in East Africa [32,33]. The dipole mode index (DMI) shows the difference between sea-surface temperature anomalies of the western equatorial Indian Ocean (10° N–10° S; 50–70° E) and the southeastern equatorial Indian Ocean (0° N–10° S; 90–110° E) and indicates the intensity of the IOD [34].

We compared the temperature anomalies with the rainfall of the corresponding month, as well as the following six months, to identify the time lag between the sea-surface temperature anomaly and the rainfall event. For NINO3.4, the best connection was observed between the sea-surface temperature anomalies one to two months prior to the reported monthly rainfall and we therefore took the average index of these two months. For DMI the strongest correlation was found between the monthly rainfall and the index of the corresponding and the prior month. We therefore used their average for monthly comparisons. As the IOD is expected to strongly influence the short rainy season (October to December) in East Africa [9,13,35], we combined the rainfall data of these three months comparing it to the average of the DMI from September to December to confirm if this is also the case for Mt. Kilimanjaro.

2.4. Focus Group Discussion

To get farmers' perceptions on climate change, we conducted twelve focus group discussions (FGDs) in March 2019, with coffee farmers from six communities on the southern slope of Mt. Kilimanjaro (Isuki, Lemira Mroma, Masama Mula, Mudio, Kiwakabo, and Mbokomu) (Figure 1). These communities work with the non-governmental organisation Hanns R. Neumann Stiftung (HRNS), who organised the farmers for the FGDs. Each FGD had between four and eight participants, with a total of 56 participants. Each group made a climate calendar marking the rainy and dry seasons in a normal year [36]. For farmers in the region, the year starts with the main rainy season. The calendars therefore start in March and continue to January and February of the following year. The groups then identified when last they experienced an extremely wet and an extremely dry year and marked the rainy and dry seasons for those particular years [36]. During analyses, a month was considered wet or dry if more than half of the FGDs indicated it as such, otherwise we considered the month neither wet nor dry. The farmers were further asked for their perception of how the climate changed in general in the last 10 years.

To learn from farmers' experiences, we discussed if and how extreme events (wet or dry) affected coffee yields and quality in the different production stages. To understand how farmers cope with climate change, we discussed adaptation strategies they employed in the past to overcome extreme weather events. We focused especially on the role of shade trees and asked what influence shade trees have on coffee productivity (yield and quality) and if it affects coffee yield variations between years. We furthermore inquired if shade density or tree species plays a role. The main points mentioned during the FGDs were identified and reoccurring concepts are presented.

3. Results

3.1. Climate Change

3.1.1. Change in Annual Precipitation

Observable from data of the past 19 years (2001–2019) is a trend of increasing precipitation at the investigated area at Mt. Kilimanjaro (22.7 mm per year; $F_{1,198} = 12.78$; $p = 0.0004$) (Figure 2). There also seems to be an increasing number of wet years and fewer dry years in recent years, including years with high or low total precipitation as well as years with longer rainy seasons or dry spells (Figure 2).

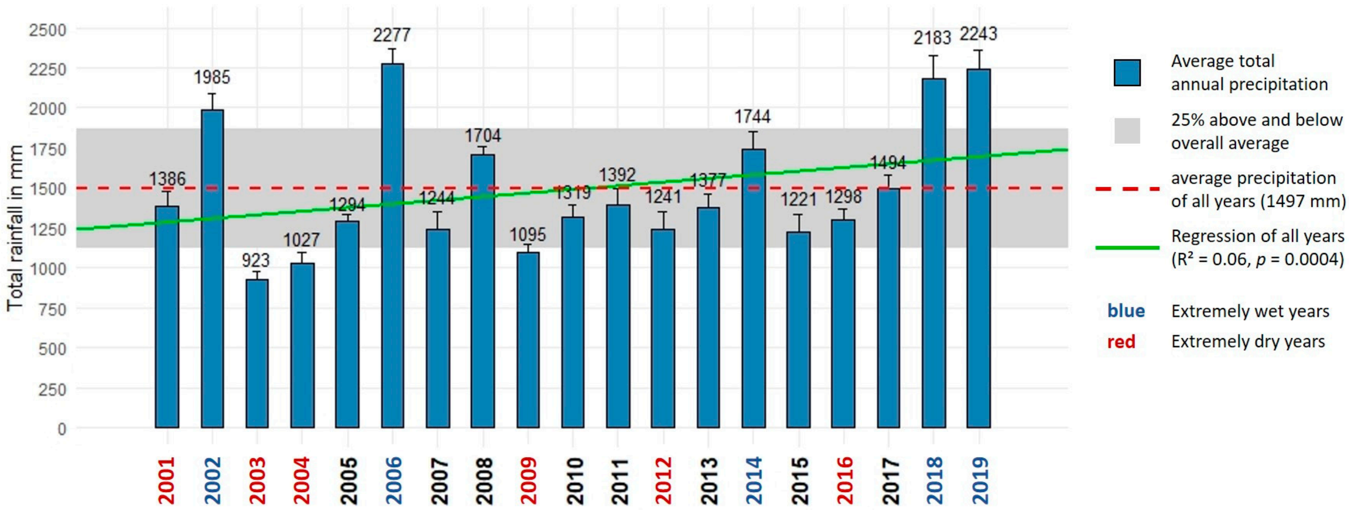

Figure 2. Average annual precipitation for all reported areas with standard error on the southern slope of Mt. Kilimanjaro. The red line shows the average precipitation for 2001–2019 and the grey bar shows 25% above and below average. The green regression line indicates the increase of precipitation for the entire period. Years with extreme rainfall or drought are marked blue and red respectively.

3.1.2. Seasonal Changes in Precipitation

Total rainfall as well as monthly rainfall distribution are important for agricultural production. Unfavourable rainfall distribution and erratic or unpredictable rainfall patterns are a significant challenge for farmers. The average monthly precipitation for 2001–2009 and 2010–2019 indicate that the main rainy season shifted from a peak in April to a peak in May (Figure 3). This is confirmed by the correlations of years and monthly precipitation from 2001 to 2019. The precipitation in May and June towards the end of the main rainy season increased significantly (r = 0.35, $p < 0.0001$; and r = 0.19, $p = 0.0076$, respectively) (Figure 3). Farmers also experience more rainfall in the short rainy season, which shifts slightly forward. September, the driest month, became wetter in recent years, as did October and November (r = 0.25, $p = 0.0004$; r = 0.25, $p = 0.0004$; and r = 0.19, $p = 0.0071$, respectively) (Figure 3).

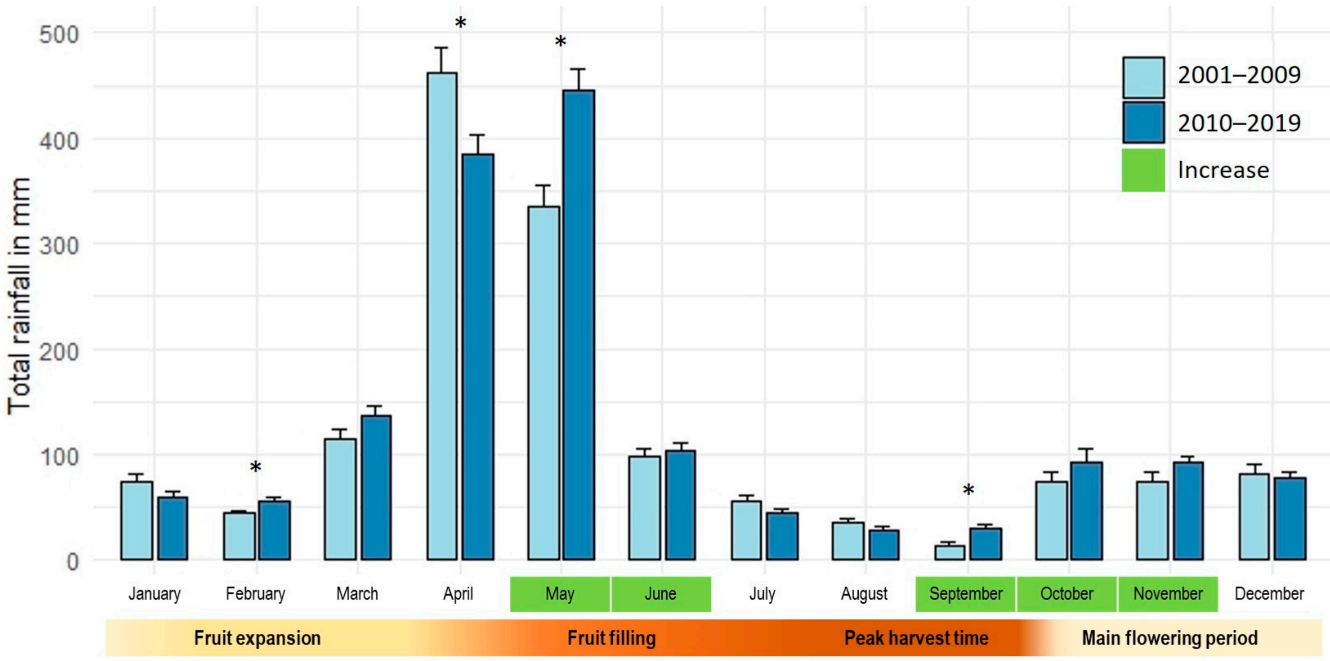

Figure 3. Average monthly precipitation for all reported areas from 2001–2009 (light blue) and 2010–2019 (blue) with standard error and significant differences indicated by * ($p < 0.05$). Months marked green show significant precipitation increases in precipitation over the last 19 years (2001–2019) ($p < 0.01$), no significant decrease was observed. The coffee development stages are shown underneath the figure.

3.1.3. Comparison with ENSO and IOD

Sea-surface temperature anomalies at zone NINO3.4 are significantly negatively associated with rainfall for March at Mt. Kilimanjaro (Figure 4a). This is a critical month for coffee production and other agricultural activities in the area, as it marks the start of the rainy season. A La Niña event (cold phase of ENSO) can reduce the rainfall amount in March, delaying the growing season. The IOD strongly influences the short rainy season from October to December (Figure 4b). A higher DMI is associated with higher rainfall at Mt. Kilimanjaro during this time. The DMI also slightly influences the rainfall in May (Figure 4c).

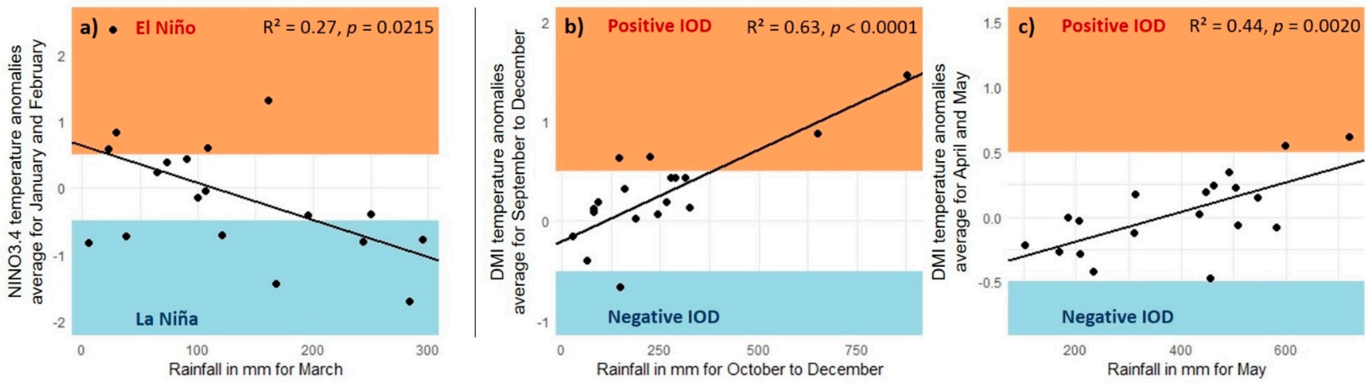

Figure 4. Correlation between sea-surface temperature anomalies and rainfall data (n = 19) for (**a**) zone NINO3.4 and rainfall in March, (**b**) DMI and rainfall in the short rainy season from October to December, and (**c**) DMI and rainfall in May. The colours indicate when temperature anomalies are classified as La Niña and negative IOD (blue) or El Niño and positive IOD (orange).

3.2. Farmers' Perceptions

3.2.1. Climate Change

There was a strong agreement among farmers that the most recent extremely wet year was 2018 with nine of the twelve FGDs reporting this. Most farmers identified 2016 as an extremely dry year (six FGDs). The only contradiction observed was for 2017, where one FGD identified it as extremely wet, while two said it was an extremely dry year. Figure 5 shows how the distribution of the dry and wet seasons identified by farmers for certain years relates to the rainfall data obtained from the coffee plantations.

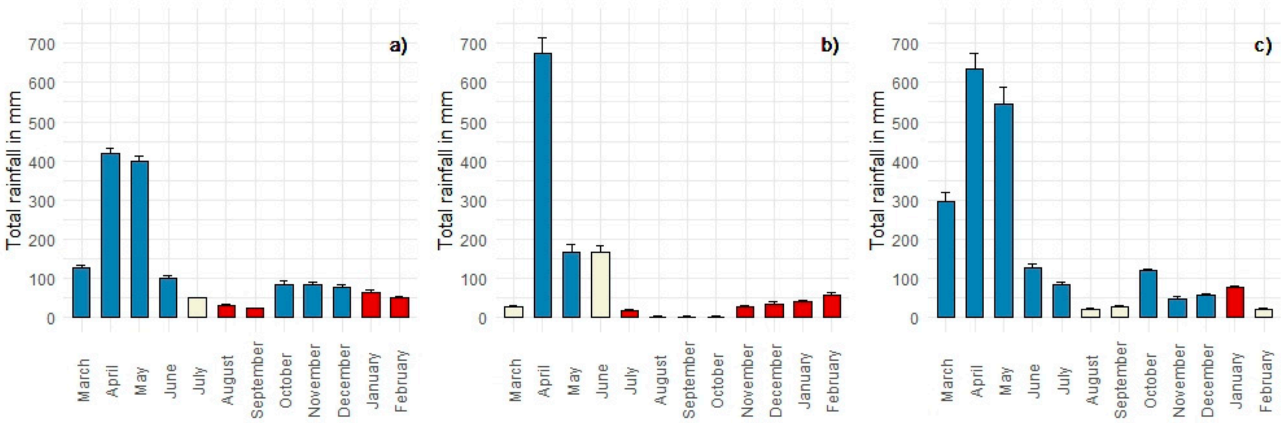

Figure 5. Average precipitation with standard error in (**a**) a normal year (average of 2001 to 2019), (**b**) a dry year (March 2016 to February 2017) and (**c**) a wet year (March 2018 to February 2019). The blue bars indicate months farmers consider wet, red bars show which months they consider dry and beige bars are neither wet nor dry.

In a normal year, coffee farmers at Mt. Kilimanjaro do not experience any extreme dry season. In extremely wet years, the duration of the rainy season as well as rainfall amounts are longer and higher respectively.

Contrary to our observations from coffee plantations' climate data, most FGDs indicated that the last 10 years except 2018 were very dry. The participants mentioned a decrease in water availability with water sources like rivers and springs drying up. Besides decreasing rainfall, they further mentioned experiencing higher temperatures, which could lead to the incidence of new insects. They reported that thrips (Thysanoptera) only appeared in the last 10 years, causing problems for coffee and other crops.

Farmers reported more extreme events and increasing unpredictability, especially of the seasons. They mentioned delayed onset of the rains, which for example was the case in 2019. This affects cultivation and causes a lot of insecurity. When the rains do start, they are heavy, damaging plants, causing erosion, floods, and destruction of infrastructure. Farmers further mentioned that weather fluctuations were on the increase. This included some years being too cold with too much rain (2018), others too hot and dry (beginning of 2019). They also reported abrupt temperature fluctuations in short periods (from very cold to very hot, typically within one or two days).

3.2.2. Impact on Coffee Production

The statements under this section are concepts and/or observations reported by farmers during FGDs. The impact of extreme events on coffee production depends on the season (Figure 6) and is explained in more detail below.

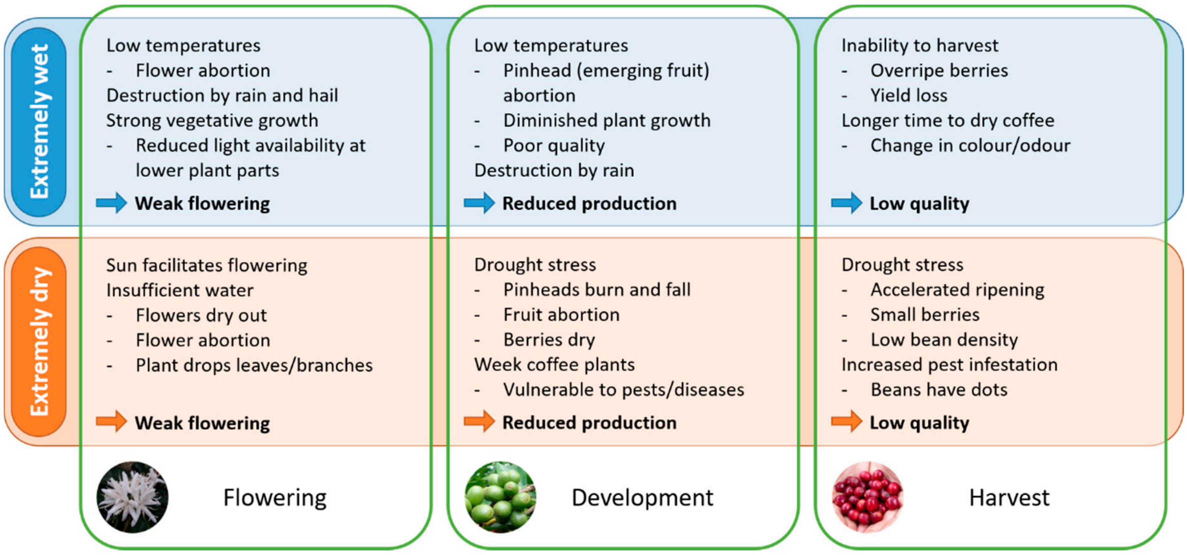

Figure 6. Influence of extreme rainfall and drought on coffee production during the different developmental stages as reported by coffee farmers at Mt. Kilimanjaro during FGDs.

It is important that coffee plants get sufficient sunlight and water during flowering; otherwise, flowering is negatively impacted (Figure 6). Some farmers reported experiencing excessive rainfall during the flowering period in 2018, which reduced the hours of sunshine and caused shade tree overgrowth, leading to excessive shading. They therefore expected low yields in 2019. Pruning shade trees as well as coffee plants can improve light availability during periods of excessive rainfall (Table A1). During droughts, irrigation is crucial to sustain flowering. A lack of irrigation capacity leads to huge losses. Farmers reported low yields in 2017 and 2018 if they could not irrigate during the flowering period of 2016 and 2017, due to the droughts experienced in these years.

Sufficient sunlight and water are also critical during the development and maturing of coffee berries. Drought and low temperatures hamper development, cause fruit abortion, and significantly reduce production (Figure 6). Farmers reported that they experienced a long drought at the beginning of 2019 during berry development, leading to massive fruit abortion and significantly reducing their expected yield.

Losses during the harvest occur, as excess rain may prevent farmers from harvesting on time, or drought accelerates the ripening process, negatively impacting on quality (Figure 6). Excessive wetness after harvesting also poses a challenge to farmers as drying the beans takes longer and may cause discolouration and/or bad odours, reducing the quality.

Extreme events increase the incidence of pest and disease infections. However, not many farmers could report details and sometimes contradictions were observed. The consent farmers reported was an increase in several pests that reproduce rapidly with excessive rains, while beneficial species like chameleons, ants and bees require warmth. Leaf rust and coffee berry disease (CBD) were reportedly a bigger problem when it is cold and wet. Leaf rust or CBD tolerant coffee varieties exist, but unfortunately they are especially susceptible to drought and only about half of the farmers plant these varieties. During droughts, coffee plants in general are more vulnerable, as the plants are easily devastated by attacks from thrips (Thysanoptera).

Farmers suggested that other challenges posed by extreme rainfall are soil erosion, flooding and water logging, which can also affect roads, making market access difficult. Farm management is a challenge during periods with extreme rainfall as routine operations like pruning, weeding or pest control cannot be carried out when due, leading to losses. Problems triggered by drought are high production costs, due to irrigation.

3.2.3. Influence of Shade Trees

Farmers at Mt. Kilimanjaro have employed several strategies to cope with extreme weather events in the past (Table A1). Potential adaptation strategies depend on the weather conditions faced (drought or excessive rains). Shade trees show some potential for managing difficult climatic conditions. On one hand, farmers are aware of many positive effects of shade trees but they also seem to understand the tradeoffs involved, which might make farmers hesitant to include more trees on their farms (Table 1). Below are experiences shared by farmers during the FGDs.

Table 1. Benefits and disadvantages of shade trees reported by coffee farmers at Mt. Kilimanjaro during FGDs.

Benefits	Disadvantages
Improve climatic conditions (lower maximum temperatures, increased humidity). Protect from direct sun. Reduce evapotranspiration.	Shade trees are negatively affected by drought, reducing shade cover for coffee plants when they most need it.
Maintain soil moisture and fertility. Reduce erosion. Provide mulch and organic matter.	
Support healthy plant growth. Promote production of beans of optimum quality (well ripe, large and heavy). Extend the lifespan of the coffee plant.	Dense shade cover reduces sunlight, negatively affecting coffee productivity.
Contribute to pest control. Provide habitats for beneficial species like bees and chameleons.	Increase in shade density, leads to an increase in pests and diseases.
Serve as windbreaks.	On strong winds, falling tree branches could damage coffee plants and/or berries.
Improve air condition (produce oxygen). Enhance local climate (increased rainfall).	

Very important considerations are the tree species and the shade density. Farmers mentioned some tree species as particularly beneficial for coffee production, especially *Albizia schimperiana* (Table A2), while others provide disservices (Table A3). Optimal shade density leads to good production and high coffee quality (optimum berry size, weight and taste). However, too dense shade provides habitats for pests and prevents sufficient sunlight from reaching the underlying coffee plants. Insufficient sunlight negatively impacts flowering, leading to production losses (some farmers reported losses of up to 90%). Poor shading and direct exposure of the soil to the sun leads to soil moisture losses due to evaporation, also negatively impacting production. Farmers suggested that both excessive and insufficient shade, affects the development of coffee berries, which remain very small and light, with an unpleasant taste.

A reduction in coffee yield variation between years due to shade trees is often reported in the literature [15,23]. However, farmers at Mt. Kilimanjaro mostly attributed variations to weather conditions such as amount and pattern of rainfall. Some farmers mentioned that high production in one year leads to low production the next year as they need to prune the old branches that produced a lot and allow the tree to develop new branches for production the next year. They reported that management practices and inputs influence yields and sometimes can explain the variations. Shade can slightly reduce yield variations as it, to an extent, buffers the effects of drought, improving productivity in dry years. However, most famers did not report this as weather condition is perceived as a more dominant factor influencing yield variations.

4. Discussion

4.1. Climate Change

There is a large regional and local variability in precipitation [5,37] and changes observed in other parts of Tanzania or East Africa do not necessarily match what farmers at Mt. Kilimanjaro experience. At Mt. Kilimanjaro, there might be localised differences, with some areas experiencing excess rain, while others do not. This can also explain the contradiction observed for 2017, where some farmers reported it as dry, while others experienced it to be a wet year. In general, however, farmers' perceptions were similar between FGDs. There was also a strong consensus with the historical rainfall data as the distribution of the rainy and dry seasons farmers reported for the different years match the rainfall distribution reported by coffee plantations (Figure 5).

Previous literature on climate change and phenomena influencing extreme weather events in East Africa corresponds to our observations. The prediction is, that annual precipitation will increase in East Africa [5,13] and we found this to be true over the past two decades (Figure 2). In contrast, farmers reported less precipitation and an increase in droughts. Similar perceptions were found in the southern highlands of Tanzania where farmers reported a decline in precipitation, a shorter rainy season, delay in the onset of rains, increased droughts and rising temperatures [38]. To understand this seemingly contradiction, it is important to look at the seasons and rainfall distribution.

The two rainy seasons at Mt. Kilimanjaro are connected to the movement of the Intertropical Convergence Zone (ITCZ) [9,39]. The long rainy season is between March and May and the short season from October to December [35]. We observed a shift of the long rainy season (Figure 3) and a correlation between the delayed onset in March and the El Niño phenomena (Figure 4a). Wainwright et al. [40] report a shortening of the main rainy season (later onset and an earlier termination of the rainy season), however with a similar total precipitation amount. They attributed it to anomalously warm sea-surface temperatures south of East Africa, delaying the northward movement of the ITCZ [40]. Even though the ENSO events have been linked to some severe droughts and floods in parts of East Africa [37,39,41], the Indian Ocean also significantly influences the regional climate extremes [9,39,42]. Extreme IOD events especially affect the short rainy season from October to December [9,13,35]. We observe a similar connection between interannual variability in precipitation of the short rainy season and the DMI (Figure 4b). In the future, with increasing global mean temperature, the frequency of extreme positive IOD is expected to significantly increase [12,13]. This can explain the increase in precipitation during the short rains already observed at Mt. Kilimanjaro.

The contradiction between a projected precipitation increase in East Africa and the shortening of the main rainy season over the last decades is described as the "Eastern African climate paradox" [40]. This explains the difference between the increases in drought observed by farmers and the increase in total rainfall shown from the data of the coffee plantations.

The rains in March are especially important for the start of cultivation and a delay negatively influences farmers. This is where successful adaptation measures are critical. Fewer but heavier rainfall events are not beneficial for plant growth and the increase in temperature needs to be considered as well. Higher temperatures accelerate evapotranspiration, which can lead to an increase in droughts [6]. Considering these changes, adaptation strategies have to provide measures to overcome droughts and shorter wet seasons with less frequent, but heavier rainfall events [7].

4.2. Effect of Extreme Events on Coffee Production

Farmers at Mt. Kilimanjaro have a very good understanding of the impact of extreme weather events on coffee production during the different development stages. Temperature increases, often reported as the driver of reducing yields, makes areas unsuitable for coffee production, pushing it into higher elevations [2,26,43]. Erratic rainfall and unpredictability of the seasons are other challenges farmers have to contend with.

Coffee flowering is triggered by the short rains in October after the dry period [18,20]. An increase in rainfall during this time as observed (Figure 3) and predicted [12,13] will prompt weak flowering, due to cold temperatures and reduced sunlight similar to in shaded conditions [15,23]. Flower abortions, increased vegetative growth and an extension of the flowering period, leading to unsynchronised berry ripening are possible consequences [2,20]. Pruning of coffee plants and shade trees during this time could help to improve light availability and support flowering.

The long rainy season from March to May on the other hand is expected to be delayed and not as substantial as it used to be [40]. This will negatively affect the expansion stage, during which rainfall is required to sustain berry development. Drought and high temperatures during this period will cause fruit abortions, increased bean defects, reduced berry growth, and acceleration of ripening, leading to a reduction in coffee yield and quality [16,20–22]. Inclusion of more shade trees might help to reduce heat stress, however, potential trade-offs due to inter-species competition needs to be considered [28].

Farmers reported some adaptive measures they already use to overcome extreme events (Table A1). These can help in finding ways of managing climate change in the future. However, more research into the feasibility and effectiveness of these measures will be required. The unpredictability of rainfall makes it necessary that farmers are aware of unexpected changes, perhaps through early warning systems. Adaptation to both extremes, droughts and floods will be necessary. Special focus should be on soil and water management to ensure better soil moisture retention during dry seasons and to reduce erosion during heavy rainfall events.

While farmers see the general challenges of weather extremes on the spread of pests and disease, their knowledge on it and especially their experience with newly occurring pests is limited. Finding a consensus on the contribution of shade trees to the spread is challenging, as it might also be context specific. A better understanding of pest and diseases that affect coffee production in this area will be required, as rising temperatures facilitate the spread of pests and diseases [24,25].

4.3. Benefits and Disadvantages of Shade Trees

Shade tree benefits and disadvantages reported by farmers are in line with those reported in literature [15,28,44]. The challenge is finding the right tree species, shade density and management practice to reduce trade-offs for coffee production, while maximizing the benefits provided by shade trees. Smallholder farmers at Mt. Kilimanjaro only grow coffee in intercropping systems with shade trees, which might explain their inability to report in detail on the effect of trees on coffee production, especially yield variation. Effects from denser shade cover and lighter shade cover were more consistent.

Farmers worldwide are very knowledgeable about the tree species on their coffee fields [45–47]. Out of the seven tree species reported as beneficial in the FGDs (Table A2), five are within the top six ranked for improving coffee production by 263 small-scale farmers at Mt. Kilimanjaro [45]. To improve understanding of the influence the different species have on microclimate, soil and coffee production, more investigations are needed.

Previous research shows that shade cover buffers temperature extremes [19,27,48,49]. The different effects on maximum and minimum temperatures and the effect of this on coffee production needs to be considered [2,16]. The required density for an optimal outcome is still to be determined. This might not only differ between locations, but also during different periods of the coffee development cycle. More research in this regard will help to improve management recommendations, especially considering the challenges of drought or heavy rainfall at different times of the year.

Including a range of diverse tree species that can provide other important ecosystem services on coffee fields could be economically beneficial for farmers [45,50–52]. Despite the potential trade-offs (yield losses in coffee production), it still might be advisable to include said trees for benefits such as additional income or food security.

5. Conclusions

This study shows that, despite observable increases in annual precipitation, farmers at Mt. Kilimanjaro are increasingly confronted with and will have to adapt to an increase in droughts as climate change progresses. This situation is caused by a shift in seasons, influenced by ENSO and IOD extremes, which results in shorter wet seasons with less frequent but heavier rainfall events. These phenomena impact coffee production during the different development stages. The adaptation of coffee production systems will therefore require strategies and/or management recommendations, tailored to specific periods of the year. More research will be required to improve our understanding of different potential adaptation measures. The focus should also be on soil and water management; especially on strategies to enhance soil moisture retention, guaranteeing plant water availability during dry seasons, and reducing erosion during periods of extreme rainfall events. More investigation is needed to quantify the effect of shade trees, including different species and shade densities, on microclimate and coffee production.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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Appendix A

Table A1. Coping measures or strategies farmers employed in extreme years in the past.

	Dry Years	Wet Year
Water management	• Irrigation with channels - agreement with other farms is required (who uses the water and when) - does not work for large farms - the channels are easily damaged and blocked by eroded soil, when there is too much water	• Create a drainage system to avoid waterlogging • Build ridges to prevent water from flowing through the farm or at least reduce the speed to reduce erosion • Water catchments to reduce erosion, which also improves moisture availability during dry season
Soil protection and fertility	• Mulch to reduce evapotranspiration and keep soil moisture • Apply cow dung as it can improve soil moisture storage • Put green leaves around coffee stem, cover it with soil and add water • Some farmers do not plough	• Plant *Cenchrus purpureus* or *Dracaena fragrans* on the edge of their farms or across the slope to reduce erosion • Mulch to reduce erosion and to suppress weeds • Plough to improve infiltration - not done frequently (maybe every 3 years) - not done when the coffee has a lot of fruits • Apply animal dung or NPK around coffee plants and cover it with soil or mulch
Shade trees	• Maintain a high shade density by not pruning shade trees • Planting more shade trees - newly planted trees might not grow properly under dry conditions	• Prune shade trees and reduce banana leaves to allow sunlight to reach coffee plants • Plant more shade trees to reduce soil erosion
Coffee tree management	• Farmers do not prune coffee branches or only very few • Prepare new places with fertilizer to plant coffee trees the next year	• Prune coffee branches to improve aeration and ensure sufficient light reaches every branch • Plant new coffee trees - a lot get damaged by rain - plant in lines to reduce erosion • Plant disease resistant coffee variety, adapted to high moisture and with low input requirement - this variety is not adapted to drought
Leaf application	• Spray booster (fertilizer with water) to apply moisture to the leaves - requires capital	• Spray coffee leaves to generate heat and prevent coffee from freezing - chemicals are expensive - local mixtures (fermented cattle urine or plant material)
Other measures	• Some apply ashes around the coffee stem to prevent ants • Many abandon the coffee farm - use the coffee plants as firewood - focus on food crops	• Weeding to reduce leaf rust • Some apply oil on coffee stem to prevent ants and stem borer • Hire people to harvest berries in a short time • Some abandon the coffee farm

Table A2. Beneficial trees for coffee production and their services reported by farmers.

<table>
<tr><th>Beneficial Tree</th><th>Services</th></tr>
<tr><td>Albizia schimperiana</td><td>coffee plants underneath get enough sunlight and produce well
has small leaves, which allow the sun to penetrate
the canopy is very high so sunlight can still reach the coffee
during the coffee flowering, it sheds leaves, which helps to get more sunlight
leaves and branches are good fertilizer and can be used as mulch
keeps soil moisture for a long time
provides habitat for beneficial insects</td></tr>
<tr><td>Croton macrostachyus</td><td>the tree canopy is very high, making good shade cover for the coffee plants
leaves and branches are good fertilizer and can be used as mulch
keeps soil moisture for a long time
deep roots
provides habitat for beneficial insects</td></tr>
<tr><td>Cordia Africana</td><td>good shade cover
covers a big area but is not too dense
leaves are good fertilizer
provides habitat for beneficial insects</td></tr>
<tr><td>Margaritaria discoidea</td><td>the tree canopy is very high, making good shade cover for the coffee tree
leaves are good fertilizer
keeps soil moisture for a long time</td></tr>
<tr><td>Rauvolfia caffra</td><td>leaves are good fertilizer and can be used as mulch
provides habitat for beneficial insects
not good for coffee trees</td></tr>
<tr><td>Commiphora eminii</td><td>leaves are good fertilizer and can be used as mulch</td></tr>
<tr><td>Ficus sur</td><td>leaves are good fertilizer</td></tr>
</table>

Table A3. Non-beneficial trees for coffee production and their disservices reported by farmers.

<table>
<tr><th>Non-Beneficial Trees</th><th>Disservices</th></tr>
<tr><td>Mangifera indica</td><td>leaves do not easily decompose
consumes a lot of water</td></tr>
<tr><td>Persea Americana</td><td>leaves do not easily decompose
consumes a lot of water
coffee trees or banana underneath this tree will not produce well</td></tr>
<tr><td>Bridelia micrantha</td><td>consumes a lot of water
coffee trees or banana underneath this tree will not produce well</td></tr>
<tr><td>Grevillea robusta</td><td>leaves do not easily decompose, cannot be used as fertilizer or mulch and are not good for the soil
consumes a lot of water
coffee trees or banana underneath this tree will not produce well</td></tr>
</table>

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