

Article

Projections of Local Knowledge-Based Adaptation Strategies of Mexican Coffee Farmers

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Abstract: Local knowledge can be a strategy for coping with extreme events and adapting to climate change. In Mexico, extreme events and climate change projections suggest the urgency of promoting local adaptation policies and strategies. This paper provides an assessment of adaptation actions based on the local knowledge of coffee farmers in southern Mexico. The strategies include collective and individual adaptation actions that farmers have established. To determine their viability and impacts, carbon stocks and fluxes in the system's aboveground biomass were projected, along with water balance variables. Stored carbon contents are projected to increase by more than 90%, while maintaining agroforestry systems will also help serve to protect against extreme hydrological events. Finally, the integration of local knowledge into national climate change adaptation plans is discussed and suggested with a local focus. We conclude that local knowledge can be successful in conserving agroecological coffee production systems.

Keywords: agroforestry; peasant; stakeholders; adaptation viability



Citation: Ruiz-García, P.; Conde-Álvarez, C.; Gómez-Díaz, J.D.; Monterroso-Rivas, A.I. Projections of Local Knowledge-Based Adaptation Strategies of Mexican Coffee Farmers. *Climate* **2021**, *9*, 60. <https://doi.org/10.3390/cli9040060>

Academic Editor: Sari J. Himanen

Received: 21 March 2021

Accepted: 6 April 2021

Published: 8 April 2021

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1. Introduction

The adaptive capacity of individuals and communities is being increasingly exercised around the world. It is common to hear about policies, laws, and strategies that encourage adaptation in almost all economic sectors. For example, the Paris Agreement [1] recognizes that adaptation is a “global goal” as important as mitigation in addressing climate change. In fact, of 119 nationally determined contributions (NDCs) received in 2015, 100 included an adaptation component [2]. Some measures have more technical and financial support than others, but there are still significant gaps and neglect in agriculture. For many countries the agricultural sector is as important as the water sector [3], and governments have failed to fully cover agricultural activity by improving resilience and capacity to adapt to climate change. Resilience focuses on the capacity of systems to prepare for and withstand shocks and stress associated with natural hazards, and in particular with the inherent uncertainties associated with the magnitude, severity, and timing of hazard impacts or climate change [4–6]. Therefore, the adaptive capacity, which is a basic component required to collectively manage the resilience of a system, has not been completely improved [7].

Mexico has made significant advances in terms of studies [8], laws [9], and regulations [10] to address climate change (also see <https://cambioclimatico.gob.mx/> accessed 10 June 2020). The country even integrates adaptation commitments into its NDCs [11]. However, these efforts are not enough to reach the poor and marginalized corners of the country. For 2018 [12], Mexico reported 82.1 million poor people (65.6%) and 7.1 million (13.3%) people working in the primary sector, which includes agriculture, livestock farming, forestry, hunting, and fishing [13]. In just under 16% of the national area, irrigated

or rain-fed agriculture is carried out [14]. In this environment, the diversity of forms of production is a challenge that has not been met by agricultural policies to address climate change. This is the case for the coffee sector in Mexico, which is already awaiting the impacts of climate change, namely temperature increases and changes in the quantity and distribution of precipitation, both of which will cause decreases in coffee yield and quality [15,16]. It is estimated that the coffee yield may decrease up to 34% [17] due to changes in coffee growth, flowering, and fruiting [18,19]. In addition, increases in the incidence rates of pests and diseases such as rust (*Hemileia vastatrix*) and coffee berry borer (*Hypothenemus hampei*) are expected [20–22]. The result will be a reduction in family income and an increase in the costs related to farming, harvesting, and processing coffee due to the risk of droughts, fires, and storms [23].

The effects of extreme weather events are also being increasingly suffered within the country. Official reports indicate that tropical cyclones and floods are the most frequent events [24,25], with the central and southern areas of the country experiencing the most damages and losses. In recent years, the country has suffered severe economic losses brought about by tropical cyclones, namely hurricanes Odile (2014); Ingrid and Manuel (2013), Alex, Karl, and Matthew (2010); Dean (2007); and Wilma and Stan (2005). Specifically, 86.8% of damages and losses between 2000 and 2018 were of hydrometeorological origin [24]. The country's farmers skillfully deal with these extreme events and climate change impacts with little or no assistance [26]. Historically, extreme events have been present in the area but coffee plantations have been able to recover [27]. However, future climate change may mean that the coffee plants can no longer recover from the impacts [28].

Nature-based adaptation and traditional knowledge strategies are based on the use of biodiversity and ecosystem services to increase the resilience of natural and modified systems to face climate change [29]. Nature solutions are considered appropriate adaptation options for small producers [30]. Traditional knowledge has been used (unplanned in some cases) in strategies to cope with extreme events and promote adaptation and risk reduction. Local knowledge is rarely taken into account in the design of modern adaptation strategies [31], but its potential is high. There are different criteria in Mexico to identify indigenous peoples or communities in population censuses [32], including definitions based on indigenous language speakers (by self-recognition), indigenous heads of households, indigenous language-speaking parents or grandparents, and others. Several studies also report that some people deny belonging to an indigenous group for personal reasons or interests of various kinds. Thus, in this paper we will focus on local knowledge, recognizing that in the communities of small producers in Mexico, there are both communities of native peoples and communities that have included their indigenous roots in their culture, particularly in their worldview and agricultural practices. Local knowledge has been shown to be a driver of successful adaptation actions, particularly among governments and informal local institutions [33]. For example, the diversification of production systems or the efficient management and use of water are traditional strategies that increase productivity, sustainability, and resilience for small farmers under different climate change scenarios [34]. Such is the case with coffee growing in Mexico, where it is estimated that 90% of the country's area dedicated to this activity uses native and introduced trees of economic interest to offer shade to coffee trees. This alternative mode of production is managed mainly by small producers and about 30 indigenous groups in the country [35]. The type of management that is carried out in most coffee farms under agroforestry systems is through traditional techniques passed down from generation to generation, with little or no agricultural technology, with the incorporation of cultural and religious elements and a different worldview on the management of their system [36]. The perception of coffee producers can lead to a better understanding of the adaptation process that is underway and its weaknesses [37]. However, there is little information on how producers are perceiving and experiencing climate change in Mexico. In addition, information is lacking on the adaptive potential of nature-based actions, such as the use of shade trees, live fences, and live barriers [38]. Knowing about this potential could help

farmers improve the sustainability and resilience of farms to climate change. However, in some regions there is a risk of losing traditional knowledge due to the migration of young people, which reduces the potential to improve the resilience of communities.

Thus, there is a challenge in incorporating local knowledge into adaptation planning. Studies are needed to rescue local knowledge in order to incorporate it into adaptation planning according to the needs of each rural community [39]. Therefore, the goal of the manuscript is to project over time adaptation strategies already implemented by farmers to evaluate their future viability in terms of carbon sequestration and water availability. We choose coffee production as it is an important crop for the country and is particularly sensitive to climate change. In Mexico, the indigenous origin of nearly 25 million people transcends and intertwines local knowledge in the communities where they live, opening up potential possibilities to exploit the diversity of adaptation strategies.

2. Materials and Methods

2.1. Organizations and Regions

The historical climate and climate change analyses were first carried out to understand the main risks facing the region. Interviews were then conducted with producers from two regions in south-central Mexico to learn about their adaptation strategies and actions. Finally, adaptations were projected to determine their future viability and to assess local knowledge. The study was conducted with two regional coffee-producing associations in the state of Veracruz: (1) the Regional Coffee Council of Coatepec A.C. (*Consejo Regional de Café de Coatepec A.C.*) and (2) the “Catuaí Amarillo” Social Solidarity Society (*Sociedad de Solidaridad Social “Catuaí Amarillo”*). The former is an organization of just over 3000 small farmers in the municipality of Coatepec and the latter is a small organization with less than 50 producers in Chocamán (Figure 1), both in the Mexican state of Veracruz. Each of the stages is described below.



Figure 1. Regional coffee-producing associations studied in the state of Veracruz.

2.2. Historical Analysis, Observed and Projected Changes

Two weather stations representing the climate of each of the regions studied were selected. One station was considered sufficient for each case due to its proximity to the studied area (less than 3 km), which meant little climatic variation. The Coscomatepec station (number 30,032) is located at 1530 masl, while the Teocelo station (number 30,179) is

located at 1188 masl. Both stations are operated by CONAGUA-SMN [in Spanish Comisión Nacional del Agua and Servicio Meteorológico Nacional (National Water Commission – National Meteorological Service)], available at: <http://clicom-mex.cicese.mx/mapa.html> accessed 10 June 2020). Daily maximum temperature (Tmax), minimum temperature (Tmin), and precipitation (Pp) data were taken from each station. In accordance with López [40], the information was subjected to a quality control process using Rclimdex (ver 1.1, CDAS) and to homogenization with RHtests (ver4). Subsequently, 27 ETCCDI climate change indices [41] were estimated using RclimDex [42]. The outputs of the climate change indices were classified into quartiles according to the observed change, as shown in Table 1.

Table 1. Classification of observed change in climate indices.

	Decrease	Increase
Low	-	+
Moderate	–	++
High	—	+++
Very high	——	++++
No changes	N/C	
No data	ND	

NC = no changes, ND = no data. Blue colors refer to decrease in observed data, yellow and red colors refers to increase.

Climate change scenarios were taken from UNIATMOS (Unidad de Informática para las Ciencias Atmosféricas y Ambientales, accessed 13 June 2020 at <http://atlasclimatico.unam.mx/AECC/servmapas>) and Cavazos [43]. The models used were GFDL_CM3 (Geophysical Fluid Dynamics Laboratory), HADGEM2-ES (Hadley Centre Global Environment Model), MPI (Max-Planck-Institut für Meteorologie), and CNRM (Centre National de Recherches Météorologiques) with a $30 \times 30''$ resolution, and Representative Concentration Pathway values of RCP 4.5 W/m² (low emissions) and 8.5 W/m² (high emissions) for the near (2010–2039), medium (2040–2069), and distant (2070–2099) time horizons.

2.3. Local Knowledge

Focus groups and semi-structured interviews [44] were conducted with small producers. The three-fold objective was to find out the main weather and climate threats perceived by producers (snowfall, heavy rain, frost, hail, strong winds, ENSO, growing season, and rainfall changes), identify the impacts they have generated on the agricultural development of coffee, and learn about the adaptation actions that farmers are already taking. The questions focused on two aspects: the strategies adopted at the individual level to deal with the threats and those promoted by the organizations to which they belong. Supplementary Material 6 shows the main questions. The study involved 25 small producers who are members of the Catuai Amarillo association and 43 coffee farmers in the municipality of Coatepec. The interviewees were selected according to their willingness to participate in the workshops.

2.4. Evaluation of Adaptation Strategies

Based on the results of the interviews, some of the individually or collectively driven adaptation strategies were selected and evaluated. In the two cases studied, field trips were made to the coffee farms to confirm what was indicated by the producers. The adaptation strategies evaluated were improvements of biomass (agroforestry practices) and protection of soil moisture (agricultural practices). We used carbon content and water balance (growing season) values as indicators of future conditions of production in agroforestry systems and for the efficient use of water. It is possible to find other variables to evaluate adaptation, however we believe the previously used ones are sufficient to technically demonstrate local knowledge and responses to climate change. By improving both variables, it will be feasible to point out that adaptation actions address risks and are viable responses.

2.4.1. Carbon Content as Indicators of Future Conditions

We used carbon content projections to evaluate potential mitigation and current adaptation strategies and their impacts over time on the health of soils and agroecosystems [45]. To calculate the carbon contents in the aboveground biomass under the current conditions, the inventory made by Ruiz [46] for 25 coffee plots was taken as the basis (see Online Resource 1) and the model for quantifying carbon sequestration CO2Fix [47] was applied. The software requires evaluation from cohorts, which are groups of individuals or species assumed to have similar growth patterns [48]. According to Schelhaas [49] and Masera [47], the carbon stored in the living biomass (C_{bt}) of the entire system can be expressed as the sum of the biomass of each cohort (Equation (1)).

$$C_{bt} = \sum C_{b_{it}} \quad (1)$$

where $C_{b_{it}}$ is the carbon stored in the living biomass of cohort “i” at time “t” (MgC/ha). The total carbon stored will be the sum of the cohorts, which depends on the stem growth and biomass, expressed as a function of the current annual increase (CAI). The CAI of each cohort is calculated based on the actual aboveground biomass over the current achievable maximum of the cohort. To calculate the simulation over time, $C_{b_{it}}$ is determined by Equation (2):

$$C_{b_{it+1}} = \sum C_{b_{it}} + K_c [G_{b_{it}} - M_{s_{it}} - T_{it} - H_{it}] \quad (2)$$

where K_c = constant for converting biomass into carbon content (MgC per Mg of biomass dry weight); $G_{b_{it}}$ = biomass growth; T_{it} = branch, foliage, and root rotation; $M_{s_{it}}$ = tree mortality due to senescence; H_{it} = harvest. More information is presented in Supplementary Material 1.

2.4.2. Water Balance as Indicator of Future Conditions

Water regulation, an ecosystem service, was projected to evaluate the impacts of current adaptation over time. The water regulation was determined following the modified Thorntwaite technique [50] to determine the monthly aridity index, soil moisture availability, and growth period. It should be noted that the climate change scenarios were applied to the base scenario in order to determine the impacts of the adaptation measures.

3. Results and Discussion

3.1. Climate and Climate Change

The areas studied have similar general characteristics—subtropical temperate summer climates, with little thermal oscillation. The highest temperatures of the year occur before the summer solstice; that is, in May. September is the month with the most rainfall. The area around Coatepec is slightly cooler than that around Coscomatepec, which is slightly further south. In summer, there are tropical air masses, eastern waves, depressions, tropical storms, and hurricanes, usually starting in June and sometimes during the second half of May [51]. In winter, from October to May, polar air masses arrive in the form of cold fronts called “nortes”, while cold air associated with the passage of polar troughs also sweeps over the region [52,53].

In the region, the beginning and end of the coffee production period largely depend on the elevation at which the plantation has been established, since it influences the temperature and moisture available for plant growth, as well as the good development and ripening of the coffee bean. The coffee plant’s phenology should be noted, including for flowering (March to April), fruit growth and development (May to October), and ripening (November to February). Even the harvest can be affected by a climatic phenomenon.

Extreme events have impacted the region in recent decades (see Supplementary Material 2). Specifically, there has been snowfall, heavy rain, frost, hail, strong winds, forest fires, and landslides. The events associated with precipitation are explained by the way in which the rainfall pattern is changing. Slight increases in the numbers of days with rainfall greater than 10 and 20 mm were observed at the two sites studied. The weather station to

the south (Coscomatepec) recorded a considerable increase in total annual rainfall, while the station further north (Teocelo) recorded less rainfall (Table 2). The rainfall pattern is becoming more irregular and increasingly stormy events are being recorded; that is, it rains a little more in fewer events. Regarding temperature, there are decreases in cold periods (days), cold nights, and cool days. Warm nights and extreme minimum temperatures are increasing. This indicates that increasingly extreme conditions, longer warm periods, and more frequent extreme minimums are occurring.

Table 2. Observed changes in trends in weather stations and adaptation actions (individual and collective).

Index	Description	Coscomatepec	Teocelo	Adaptation Actions *	
				Individual	Collective
CDD	Maximum length of dry spell	-	+	Living fences	Use of agroforestry systems
CSDI	Cold spell duration index	—	+++		
CWD	Maximum length of wet spell	—	+	Living barriers	
DTR	Daily temperature range	-	+		
FD	Number of frost days	S/N	+	Use of agroforestry systems.	
GSL	Growing season length	-	-		
ID	Number of icing days	S/N	S/N		
PRCPTOT	Annual total precipitation in wet days	++++	—	Living barriers and fences	Use of agroforestry systems with trees that do not compete for water resources with coffee.
R10 mm	Annual count of days when PRCP ≥ 10 mm	++	+		
R20 mm	Annual count of days when PRCP ≥ 20 mm	+	-		
R95p	Annual total PRCP when RR > 95p	—	+	Use of agroforestry systems with trees that do not compete for water resources with coffee.	
R99p	Annual total PRCP when RR > 99p	—	—		
Rnnmm	Annual count of days when PRCP ≥ nn mm	+			
RX1day	Monthly maximum 1-day precipitation	—	-	Use of agroforestry systems with trees that do not compete for water resources with coffee.	
RX5day	Monthly maximum consecutive 5-day precipitation	—	++		
SDII	Simple precipitation intensity index	+	-		
SU	Number of summer days	+	+++		
TN10p	Percentage of days when TN < 10th percentile (cold nights)	—	++	Tree shade regulation (40–80%)	
TN90p	Percentage of days when TN > 90th percentile (hot nights)	++	+		
TNn	Monthly minimum value of daily minimum temperature	++	-	Tree shade regulation (40–80%)	
TNx	Monthly maximum value of daily minimum temperature	+	-		
TR	Number of tropical nights	-	+		

Table 2. Cont.

Index	Description	Coscomatepec	Teocelo	Adaptation Actions *	
				Individual	Collective
TX10p	Percentage of days when TX < 10th percentile (cold days)	–	–		
TX90p	Percentage of days when TX > 90th percentile (hot days)	+	++		Use of agroforestry systems. Tree shade regulation (40–80%)
TXn	Monthly minimum value of daily maximum temperature	+	+		
TXx	Monthly maximum value of daily maximum temperature	–	+		
WSDI	Warm spell duration index	+	++		

Note: * adapted from responses given in focus groups and semi-structured interviews. Blue colors refer to decrease in observed data, yellow and red colors refers to increase.

Climate change scenarios indicate that precipitation levels in winter, spring, and summer will decrease for the 2070–2099 horizon by 15%, 14%, and 18%, respectively. In autumn, an increase of up to 13% is expected. Regarding the annual balance, a –6% variation in the above-mentioned period is possible. Regarding the maximum temperature, the scenarios indicate that it will increase throughout the year to 1.5 °C in the near (2010–2039), 3 °C in the middle (2040–2069), and up to 4 °C in the distant (2070–2099) future. Increases of 1, 2, and up to 3 °C in minimum temperature are projected for the same time horizons (see Supplementary Material 3).

3.2. Local Knowledge on Adaptation to Extreme Events

The weather and coffee production are carefully monitored by farmers. Based on the opinions of those interviewed the last few years have been different in relation to average climate conditions. Producing coffee in the region means coping with climate changes and solving marketing problems.

Regarding the observed climate changes, most farmers agreed during the interviews that they are experiencing more prolonged droughts (now from June to November, before April to May). In relation to the mid-summer heatwave, colloquially known as the “dog days” (“canícula” in Spanish) of summer and marked by a brief reduction in rainfall in July–August, which now occurs over a longer period, starting as early as May or June. The consequences if it lasts until September are the appearance of pests such as “palomilla” or stem borer (*Hammatoderus maculosus* Bates, 1880), “ojo de gallo” or rooster eye (*Mycena citricolor* Berkeley & Curtis), “antracnosis” or anthracnose (*Colletotrichum coffeanum* Noack), and stem rot (*Erythricium salmonicolor* Berk. & Broome). The phenomenon is known as “caniculón” (strong “canícula”). The increase in pests and diseases observed by farmers in this study coincides with what other researchers have reported in different coffee growing regions of Mexico and Latin America [20–22], who agree that the increase in temperature and changes in precipitation favor the development of pests and pathogens, which directly affect the coffee.

The presence of strong, warm winds in May to August are known as “suradas” (strong wind coming from the south) and affect the growth and development of coffee. The farmers also pointed out during the interviews that heatwaves (in March–April or even May) result in wilting of the flowers and drying-out the coffee trees. The cold fronts, called “nortes” (cold wind coming from the north), occur from September to March, affecting the coffee bean in its growth and ripening stages.

Hailstorms occur from March to May and are more frequent in summer, causing damage to leaves and fruits of coffee plants. The pest that most plagues the region is the coffee berry borer (*Hypothenemus hampei*, Fer.), which appears during the ripening of the fruit (July until September). The coffee berry borer is a beetle measuring just 2 mm in length. In the interviews, some producers stated that rising temperatures in the region

have expanded the pest's distribution area to increasingly higher regions above 1000 m above sea level, where it was less frequently found before.

The increased temperature makes it easier for several generations of the pest to reproduce each year [54]. Infestation is greater in humid, shady plantations compared to those that are dry and exposed to air currents [55,56]. Therefore, the increase in irregular precipitation events may function as a triggering factor for the emergence of the coffee berry borer and its spread.

Rust is another major phytosanitary problem with coffee. It is caused by the fungus *Hemileia vastratix* Berk. and Br., which attacks the leaves and can cause total defoliation of the coffee trees, consequently resulting in no harvest occurring [57]. Temperature is a determining factor for its appearance; it has been reported that its presence is sporadic at elevations higher than 900 m above sea level. However, climatic conditions have been changing and it is now possible to find outbreaks at higher elevations. People mentioned in the interviews that the disease occurs in the rainy season, starting in September.

Regarding the economic crisis that has beset coffee producers, the disappearance of the Mexican Coffee Institute (1958–1989) marked the government's abandonment of the producers. It also induced migration by the youngest inhabitants, mainly to cities. The small farmers who remained had to adjust their local production methods [58]. In the two areas studied, the farmers decided to group together. In the case of Coatepec, coffee farmers have organized themselves into the Regional Coffee Council of Coatepec A.C., which covers just over 15 municipalities. The organization began in 1996 and covers a little more than 3000 small and medium-sized farmers. For the other case study in Coscomatepec, the organization "Catuai Amarillo" is made up of small farmers who have been organized since the early 1990s and who together have 50 ha of shaded *Coffea arabica* L. production fields. Both organizations stated that they are producers of high-quality organic- and fair-trade-certified coffee.

Since then, the two organizations have been instrumental in improving the adaptive capacity and adapting to the increases in various extreme events in the study area. Agronomic soil conservation practices that promote resilience are culturally transmitted between generations, from parents to children—they are used to maintain crop residues, maintain trees in the plots, and in replacement of sick or old trees. In any case, behind soil conservation is the promotion of adaptive capacity. The organized farmers of the region, armed with their traditional knowledge, created technological alternatives to enter the market and promote organic and fair trade coffee. This is an alternative development path that generates a reduction in vulnerability to climate change [31]. Organized producers enjoy benefits such as reducing production costs, sharing experiences, and obtaining benefits from the synergies caused by the grouping, thereby stabilizing the community way of life and reinforcing sustainable alternative development [59]. In this sense, the results of the interviews are grouped into two ways of addressing the challenges of coffee production, namely individually-driven and collectively-driven actions.

In collective adaptation actions dealing with climate change, it was found that the organizations have promoted the maintenance of production in agroforestry systems and the efficient use of water.

Agroforestry systems. The permanent use of coffee agroforestry systems with diversified species of multipurpose trees and shrubs represents a primary adaptation strategy in the area. This is a very common ecosystem-based adaptation strategy that has been identified in various coffee growing areas [23,30,38]. This activity has been passed down from generation to generation among the indigenous communities of the region, with little or no agricultural technology, due to the lack of economic resources and the marked relief that hinders access to coffee plots in some cases [60,61]. Small producers in the studied communities have a different worldview on the management of coffee agroforestry systems, allowing local sustainable development of family units [36]. Recently, multipurpose trees began to replace old trees that were only used for their shade.

About 50 multipurpose species used for coffee shade in the study regions have been recorded [46]. The diversity of trees and shrubs within the coffee plantations protects the crops against the increase in recurrent extreme phenomena in the evaluated areas (intense rain, prolonged droughts during the mid-summer heatwave season, frosts and hailstorms); it also creates greater adaptive capacity, since there is no longer a total dependence on the coffee bean. In the event of a drop in the price of coffee beans or low production caused by pests or diseases, the producer can obtain economic income from the sale of other products generated within the agroforestry system [62].

Efficient use of water. The small farmers interviewed are aware of the importance of water resources, making efficient water use one of their top priorities. Within the agroforestry systems, producers use tree and shrub species that do not demand much water to avoid competition for water resources with the coffee plants. The species they mostly use are *Lippia myriocephala* Schltdl. and Cham and *Inga vera* Willd. They avoid using *Trema micrantha* (L.) Blume because they assert that it competes with coffee for soil moisture [63]. Shade regulation within the coffee plantation is also essential for efficient water use. According to the producers interviewed, 95% of the coffee farms have between 40–80% shade cover, which helps to avoid water stress on the coffee plants when long heatwaves occur. According to Lin [64], 60–80% shade cover decreases soil evaporation rates and coffee transpiration demands because it affects the microclimate and the radiant energy within the system. Outside the coffee farms, producers make efficient use of water in the coffee processing stage (washing and pulping), as they reuse the water to irrigate the coffee seedlings and the multipurpose trees and shrubs produced in the organization's nursery. This water is also used in the solid waste composting process for the production of the organic fertilizer used on the coffee farms. With projected decreases in precipitation in drier climates, the use of a simple water protection measure will become even more essential, meaning the efficient use of water represents an adaptation strategy based on ecosystems of importance in coffee plantations [23].

In relation to individual adaptation actions taken to address climate change, examples of living fences and barriers were found.

Living fences. Just over half of the producers interviewed use living fences to delimit the ownership of their plots. It is common for thunderstorms to occur in the study area, sometimes knocking down trees and branches, thus damaging fences. The use of living fences as an adaptation strategy in the face of the threat of extreme rainfall reduces the establishment and maintenance costs compared to dead fences [65].

Living barriers. Another adaptation action taken to reduce the impact of heavy rains is the use of living barriers. The farmers use various species of the genus *Bursera* sp. along the contour lines. The use of living barriers reduces soil loss due to water erosion by slowing down the speed of downstream runoff water; it also favors the sedimentation of soil particles on the upper parts of the living barriers and the formation of natural terraces [66]. With this strategy, the soil degradation process caused by heavy rains is reduced.

Reforestation, increases in protected area surfaces, and stricter forest management regulations were other key measures that coffee producers cited as possible means of preserving the regional climate. Without a doubt, the challenges posed by producers are greater than those answered; poverty, access to health services, and education are other challenges that they indicated require attention. They require support with technical assistance to continue production without losing yields.

3.3. Carbon Content Projections for Future Conditions

Current carbon levels in the aboveground biomass and the projections of carbon stocks and fluxes in the aboveground biomass were obtained for three agroforestry designs that included collective and individual adaptation actions, which were identified through field visits to the coffee plots and interviews with producers: agroforestry design 1 (Af1), involving coffee plants with shade trees and living barriers; agroforestry design 2 (Af2), involving coffee plants with shade trees, banana trees, and living barriers; and agroforestry design 3

(Af3), involving coffee plants with shade trees, banana trees, and living fences. The species found and the density of each design are described in greater detail in Supplementary Material 4. The use of agroforestry systems that includes shade trees for coffee plants corresponds to the collective adaptation actions carried out by small producers. Those that include living fences and barriers correspond to individual adaptation actions taken by producers.

The carbon content in the current aboveground biomass was the highest in Af1 with 32.20 Mg ha^{-1} and was similar in Af2 and Af3, reaching $25.52 \text{ Mg C ha}^{-1}$ and $25.69 \text{ Mg C ha}^{-1}$, respectively. These results are within the range of 20.9 to 31 Mg C/ha^{-1} reported for the aerial biomass in similar conditions to the study area [67,68].

The projected total carbon stocks in the aboveground biomass on the basis of a 50-year simulation (Table 3) showed a lower level in Af3 ($70.88 \text{ Mg C ha}^{-1}$) than in Af1 and Af2 (85.98 and $88.11 \text{ Mg C ha}^{-1}$, respectively). The inclusion of shade trees in the coffee plots accounted for 75% of the total carbon in the aboveground biomass in Af1 and Af3 and 79% in Af2. Living fences used as adaptation measures accounted for 7% of the total carbon in the aboveground biomass in the Af1 and Af2 designs. The use of living fences accounted for 16% of the total carbon in the Af3 design.

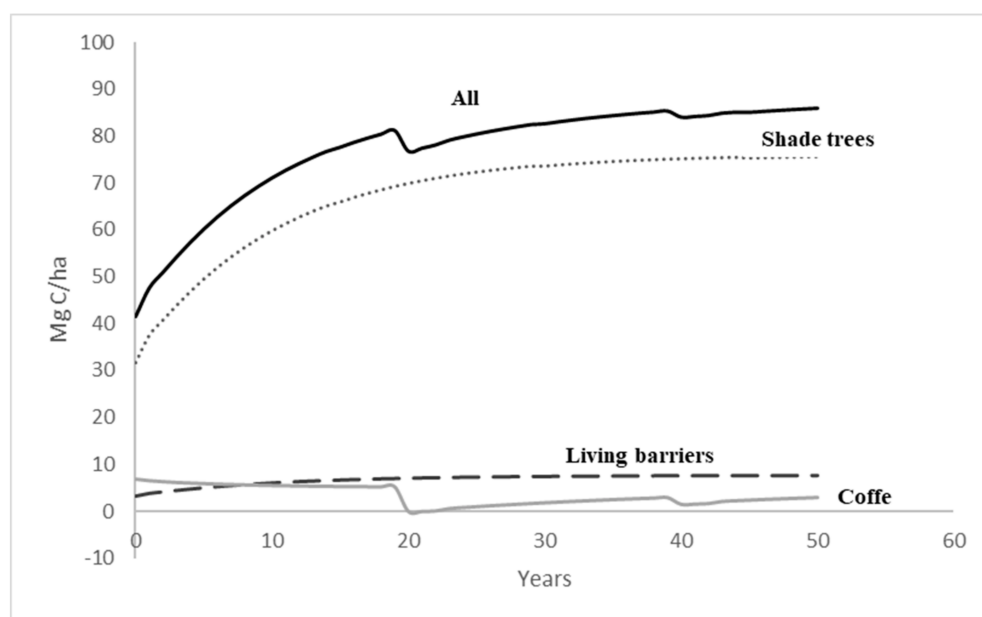
Table 3. Carbon stocks in aerial biomass (Mg C ha^{-1}) projected for 50 years according to agroforestry designs (Chocamán, Veracruz).

Agroforestry Design	Carbon Stocks					
	Coffee	Shadow Trees *	Banana Tree	Living Barriers	Living Fences	Total
Af1	2.90 ± 3.51	$75.52 \pm 43.99^{**}$	—	7.55 ± 4.39	—	85.98 ± 46.39
Af2	1.18 ± 0.76	78.90 ± 52.12	0.13 ± 0.41	7.89 ± 5.21	—	88.11 ± 57.38
Af3	1.45 ± 1.13	53.41 ± 22.07	0.69 ± 0.32	—	16.02 ± 6.62	70.88 ± 28.61

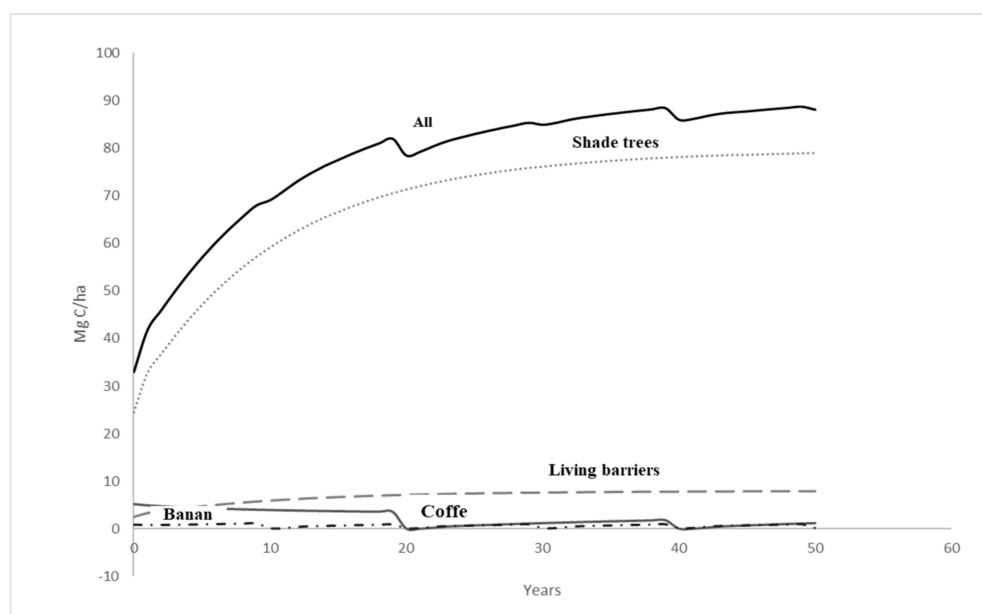
* Shade trees (see SM1 and SM4); ** SD (Mg C ha^{-1}).

The 50-year projection of carbon fluxes in the aboveground biomass is shown in Figure 2. According to what was stated in the interviews, a reduction in plant density was considered due to the rotation of coffee and banana plants every 10 and 20 years. Thus, the potential for carbon sequestration in the aboveground biomass by incorporating collective and individual adaptation responses is 96.62% for Af1, 98.66% for Af2, and 97.95% for Af3. Responses taken by coffee farmers suggest that they will increase biomass while sequestering more carbon over time. The results are similar to those projected in other coffee agroforestry systems with banana ($76\text{--}122 \text{ Mg C ha}^{-1}$) by Negash and Kanninen [69]. It should be noted that in sun-grown coffee crops, $2.76 \text{ Mg C ha}^{-1}$ is captured in areas surrounding Huatusco, Veracruz, Mexico [67]. As expected, the carbon content in the aboveground biomass in the present study is higher.

The adaptation strategies selected by farmers contribute to forming more aboveground biomass, which conserves carbon in trunks, roots, leaf litter, and dead branches. This helps carbon to be retained in the deepest soil layers, with a -4.5% loss rate [70]. In addition, the use of these adaptation actions helps in water retention, regulation of hydrological cycles, and protection against extreme weather events in the system [71].

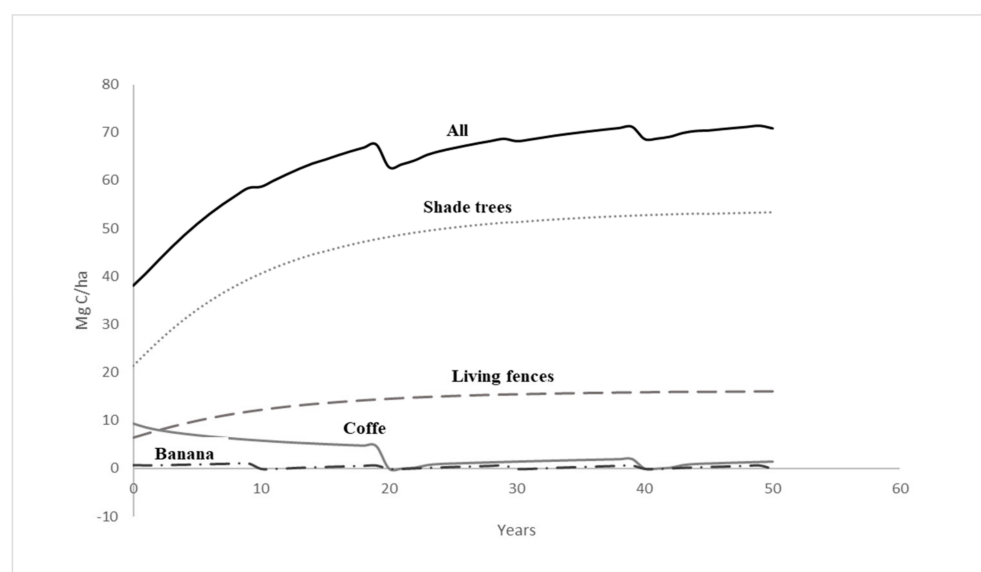


(a)



(b)

Figure 2. Cont.



(c)

Figure 2. Projections for 50-year carbon contents (Mg C ha^{-1}) in aerial biomass samples for (a) agroforestry design 1 (Af1), involving coffee plants with shade trees and living barriers; (b) agroforestry design 2 (Af2), involving coffee plants with shade trees, banana trees, and living barriers; and (c) agroforestry design 3 (Af3), involving coffee plants with shade trees, banana trees, and living fences.

3.4. Water Balance Projections for Future Conditions

Regarding water balance variables, it was found that the rainfall pattern will continue to be irregular, with consequences for agricultural production. The start of the growing season will be delayed by up to one month, while its end could be brought forward by up to three months; that is, the rainy season will become shorter, with a high risk of more stormy rain events. The durations of the growing period and the wet period will be reduced by 100 days on average (Table 4). The monthly balance indicates that the moisture stored in the soil will also decrease. The winter months will be those in which the greatest reductions are expected (see Supplementary Material 5).

Table 4. Changes in growing season variables.

	Current	Climate Change RCP 8.5 by 2099			
		CNRM	GFDL	HADGEM	MPI
Growing season starts	12-May	19-April	28-April	23-April	25-May
Growing season ends	19-April	5-January	20-February	8-January	2-November
Growing season length (days)	349	298	321	300	97
Humid period length (days)	256	182	206	206	36

See Supplementary Material 3 for climate change scenarios of precipitation. GFDL is for Geophysical Fluid Dynamics Laboratory model; HADGEM for Hadley Centre Global Environment Model; MPI for Max-Planck-Institut für Meteorologie model and CNRM for Centre National de Recherches Météorologiques model.

The adaptation strategies used by farmers also protect the soil moisture [72]. In the areas studied, coffee is rain-fed, so a deficit or excess of water in the soil modifies the phenological responses and subsequent coffee production [73]. The adaptation actions promoted in the region—both collective and individual—have shown the potential to reduce the impacts caused by decreases in the moisture stored in the soil in the dry months. The presence of trees within the agroecosystem generates the phenomenon known as hydraulic lift, whereby trees take water from deep soil horizons and redistribute it on the surface when environmental conditions are dry [74]. The water extracted by the trees can then be used by the coffee plants, thereby reducing the impacts caused by the decrease

in moisture content in dry periods projected due to climate change. The same situation occurs when the start of the rainy season is delayed.

The agroforestry strategies used, namely living fences and barriers, incorporate organic matter into the soil, involving significant water infiltration and storage, and they also prevent the destruction of aggregates and the drying of the soil [75]. Additionally, by regulating the microclimate, canopy trees in agroforestry systems help to control the water balance by influencing the system's radiant energy, which affects soil evaporation and leaf transpiration [76]. Coffee plants under full sun are exposed to higher radiation, so they experience higher temperatures and less relative humidity, causing higher transpiration rates [61]. The use of shade trees means that the coffee trees receive less direct light and experience lower air temperatures and higher humidity, losing less water due to transpiration [64].

4. Conclusions

The current capacities of coffee farmers are being diminished by more frequent and intense extreme weather events, and climate change may reduce them further. However, farmers are learning to cope with the changes with the greatest asset they have—their traditional and local knowledge. Through time and for generations, communities have passed down their knowledge from parents to children. Our results show that the adaptation strategies of local farmers are viable and fulfill many purposes.

The potential for carbon sequestration in aboveground biomass projected over 50 years demonstrates the relevance of collective and individual adaptation actions by small farmers based on local knowledge. However, further studies are needed to understand the potential for total carbon sequestration, considering the reservoirs of soil organic matter. Proposals aimed at improving the system's design to enhance the adaptive capacity of small producers in the study region are also required.

Local knowledge inherited from the country's indigenous origin (through ancestral experiences, stories, and life lessons) has shown producers that it is necessary to be well organized to cope with and adapt to climate change. The renewal of indigenous knowledge, such as traditional ecological knowledge, can bring local communities together to strengthen their own planning to address climate change [77]. Both a small local organization (Catuai Amarillo, 25 producers) and a large one (Consejo de Café de Coatepec, more than 3000 producers) share success stories of strategies that enable them to deal with extreme events and climate change. The two local organizations, regardless of size, provide the space for producers to share experiences. This is an opportunity for national and regional governments to link with producers and support better adaptation strategies, and there is an urgent need to incorporate local knowledge into national climate change adaptation policies.

The local knowledge-based adaptation strategy includes crop diversification and improved system management strategies. The producers' understanding of the change in climate variables and traditional knowledge help to generate better adaptation strategies that reduce vulnerability to climate change in the coffee sector [78]. Adaptation strategies provide more benefits besides coping with climate change; for this, we used carbon content (our results showed that carbon will improve over time) and water balance (our results showed that water availability will be reduced) as indicators. Thus, the adaptation strategies were well selected.

Coffee farmers are aware of climate variability and have noticed firsthand the increase in temperature and reduction in precipitation. As the coffee plantations are immersed in the cloud forest, an ecosystem rich in biodiversity, the farmers feel and act as though they are guardians for its conservation.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/cli9040060/s1>, Supplementary Material 1. Calculation and variables used by CO2Fix model. Supplementary Material 2. Weather events recorded in media from 1970 to 2013. Supplementary Material 3. Climate change scenarios of precipitation, maximum, and minimum temperature with RCP 8.5 for Chocamán, Veracruz. Supplementary Material 4. Cohort species by agroforestry design in coffee plots. Supplementary Material 5. Water balance variables—current and future monthly humidity index and soil moisture storage, RCP 8.5 by 2099. Supplementary Material 6. Main questions guide for interviews.

Author Contributions: Conceptualization, P.R.-G., C.C.-Á., and A.I.M.-R.; data curation, P.R.-G.; investigation, P.R.-G., J.D.G.-D., and A.I.M.-R.; methodology, P.R.-G., C.C.-Á., J.D.G.-D., and A.I.M.-R.; writing—original draft, P.R.-G., C.C.-Á., J.D.G.-D., and A.I.M.-R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding. P.R.G. received a grant from Consejo Nacional de Ciencia y Tecnología (CONACYT). The APC was funded by Universidad Autónoma Chapingo.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available upon reasonable request from the corresponding author.

Acknowledgments: P.R.G. thanks the grant by CONACYT. All authors thanks Universidad Autónoma Chapingo (CIRENAM, DGIP, Departamento de Suelos y Fitotecnia) and Universidad Nacional Autónoma de México (CCA). We gratefully acknowledge the comments and suggestions of the anonymous reviewers, whose comments have substantially improved the paper.

Conflicts of Interest: The authors have no conflict of interest with any person or institution.

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