



# New Varieties of Coffee: Compromising the Qualities of Adaptive Agroforestry? A Case Study From Southern Mexico

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The most recent wave of coffee leaf rust, and its interaction with climatic variability, caused severe crop losses in shade-grown coffee areas in Latin America during the 2010–14 production cycles and beyond. Fungal attack on traditional Arabica varieties led to a process of substitution with new coffee varieties that are tolerant or resistant to the pathogen. The adaptation literature classifies this type of intervention as an incremental adaptation, with the potential to lead the system toward sustainable transformation. This research explores the initial consequences of introducing certain hybrid varieties into the transboundary area of the Tacaná Volcano, located between Chiapas and Guatemala, with the objective of identifying aspects that put the potential for adaptive agroforestry at risk. We hypothesize that the interaction of a range of economic, political, and ecological factors leads to ambiguous results in terms of both production and environmental adaptation. Ecological and management variables were analyzed in a case study of 30 producers. Quantitative data, collected through ecological plot sampling and application of a socio-productive survey, was complemented with ethnographic data. We conclude that, for our case study, the manner in which these new coffee varieties were introduced raises new sources of vulnerability that could be compromising the local and ecological benefits of agroforestry systems, as well as diminishing their capacity to cope with the future impacts of climate change.

**Keywords:** adaptation, benefits, coffee agroforestry systems, climate variability, coffee leaf rust, new coffee varieties

## INTRODUCTION

The climate crisis poses one of the most significant challenges to sustainable coffee agriculture (Bunn et al., 2015), not just in the long-term but also at present. The main source of risk for Latin-American agriculture is increasing inter-annual climatic variability (Hansen et al., 2007). Adaptation, in its many variants, is therefore essential for both present and future conditions.

Different climate model projections agree that the area suitable for coffee cultivation in Central America and southern Mexico will reduce significantly (Gay et al., 2006; Hannah et al., 2017; Imbach et al., 2017)—climate scenarios project conditions that would favor the propagation of illnesses and pests (Bebber et al., 2016). Drier conditions and intense but shorter precipitations will extend the distribution of pathogens that attack coffee crops (Hannah et al., 2017).

Coffee leaf rust is a disease produced by the fungus *Hemileia vastatrix*. The last epidemic of this disease, which took place during 2010–2014 across Mesoamerica as well as in Colombia and Peru, illustrates the trend described above. Coffee-producing countries in Latin America experienced a severe attack by this fungus that affected coffee at elevations that had previously been free of rust. However, the spread of the disease cannot be fully attributed to climate variability (Avelino et al., 2015; McCook and Vandermeer, 2015). The interplay between changing weather patterns and constraints on crop management in a context of financial hardship exacerbated the impact of the epidemic (Renard and Larroa Torres, 2017). Crop losses, abandonment of coffee cultivation and migration were rampant across the region. The devastation caused by coffee leaf rust aggravated the precarious economic situation of the Latin American coffee producers and once again highlighted coffee's social and economic importance in this region of the world<sup>1</sup>.

This disease has been present in the coffee agriculture of Latin America since the 1970s and has prompted research exploring resistant or tolerant coffee varieties in a kind of co-evolutionary cycle (McCook and Vandermeer, 2015). However, current economic and social conditions, local environmental degradation and climate change produce an unprecedented combination of vulnerabilities, emphasizing the need to adapt to multiple sources of stress. In order to achieve a sustained adaptation outcome, unexpected negative and counterproductive adaptive actions must therefore be foreseen (Eriksen et al., 2011). Adaptation literature classifies introducing the introduction of new hybrid varieties of coffee varieties as an incremental adaptation (Fedele et al., 2019). In principle, one single adaptive practice has the potential to unleash a chain of adaptive results.

This article aims to investigate, in the context of increasing climate variability, whether introducing new coffee varieties in order to cope with coffee leaf rust could be encouraging some facets of adaptation while simultaneously hindering others. Our research focuses on coffee agroforestry systems (CAFS) in Mexican municipalities around the binational Tacaná Volcano, located between Chiapas and Guatemala. We examine the extent to which substitution of the traditional plants in smallholder coffee farmers' plots at the Tacaná Volcano acts to enhance pathways of transformative adaptation.

We draw on a case study in which we analyze the advantages and obstacles encountered while introducing the new varieties, by comparing two groups of farmers with different levels of hybrid introduction. We focus on management changes made

<sup>1</sup>In Central America, coffee accounts for 20% of foreign exports, and its cultivation occupies more than 1 million hectares. Small producers account for 80% of coffee growers, a high percentage of which live below the poverty line. Coffee supports 1.8 million jobs (Canet et al., 2016). More than 50% of the total coffee producing area in Central America was affected and production in the 2012/2013 harvest was reduced by ~20%, increasing food insecurity for more than 157,000 families in Honduras, Guatemala, and El Salvador (Canet et al., 2016). In Chiapas, ~180,000 families live on coffee-related incomes. Of these families, 61% are indigenous. Chiapas is also the state with the largest cultivated area of coffee in the country (35%, 252,744 ha) (INCAFECH, 2019) and, in 2018, it accounted for 41% of the total coffee produced in Mexico (INCAFECH, 2019). It is also the leading state in organic coffee production (73%) in the country, while Mexico as a whole is the world's second-largest producer of organic coffee (SIAP, 2015).

to adjust to the different requirements of the new plant and on the preferences of the coffee farmers in terms of bean quality and productivity. We also search for factors that compromise the adaptation of agroforestry to high climate variability. Key variables, such as shade management and soil cover, were therefore selected in order to indicate potential erosion problems. We hypothesized that the introduction of new coffee varieties will lead to differentiated management between the two groups. Hybrid varieties require a higher level of input and labor in order to manifest their associated benefits: higher productivity, resistance to rust and better adaptation to extreme weather patterns. A more intensive management is therefore required to maintain these adaptive qualities.

The paper is structured as follows: section Coffee Agroforestry Systems and Pathways to Adaptation briefly presents the link between agroforestry and adaptation, along with the main criticisms raised with respect to the dominant approach to adaptation. It also introduces the adaptive potential of new coffee varieties. Section Case Study gives the background of the case study—the substitution of traditional coffee varieties for new varieties in two groups of producers—and details the combined quantitative-qualitative methodological approach. Section Results presents the empirical results, with an emphasis on the quantitative data. Section Adaptation Between Productivity and Agroforestry Benefits: Complementing Quantitative Data With Readings From Ethnographic Data builds a narrative drawn on a summary of the ethnographic data. Section Discussion and Final Remarks discusses and interprets the overall results through an adaptation lens to determine the extent to which the adaptive benefits of agroforestry, and those of the new varieties presented in section Coffee Agroforestry Systems and Pathways to Adaptation, were fostered or hindered. It also concludes with a reflection on the adaptive implications of our case study and raises some elements that could act to encourage a potentially transformative adaptation.

## COFFEE AGROFORESTRY SYSTEMS AND PATHWAYS TO ADAPTATION

The adaptive qualities of agroforestry have been extensively studied in the specialized field of climate change adaptation<sup>2</sup> (Nair, 1997; Akamani, 2016; Gomes et al., 2020). In particular, research has shown the potential of coffee agroforestry systems (CAFS) to reduce the impact of pests and diseases (Cerdeira et al., 2020) and to preserve soil carbon and biodiversity (Soto-Pinto et al., 2002; Baca et al., 2014; Läderach et al., 2017). The CAFS have been subjected to different adaptation approaches, especially ecosystem-based adaptation (Nalau and Becken, 2018) and community-based adaptation (c.f. McNamara and Buggy, 2017 for review of the concept). These approaches focus mainly on the environmental dimension of adaptation, introducing

<sup>2</sup>The standard definition of climate change adaptation conceives it as an “adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory, autonomous, and planned adaptation” (IPCC, 2007: 869).

sustainable agronomic practices and fostering rural development planning, with an emphasis on the local scale (c.f. Vignola et al., 2015; Harvey et al., 2018; Chain-Guadarrama et al., 2019). Hence, they aim to move the system toward greater resilience in terms of the environment and climate.

Within this field of inquiry, adaptive practices are categorized on a scale according to their intensity and capacity to drive a social-ecological system toward a new state that, in turn, leads to sustainability (Pelling et al., 2015). Introducing disease-resistant coffee varieties is considered an intermediate level of adaptation and one that could unleash a series of cumulative changes in the socio-environmental system (Fedele et al., 2019). In theory, this degree of adaptation opens the door to changes that lead the system to a new equilibrium and state of resilience; i.e., to transformative adaptation.

The last epidemic wave of coffee leaf rust provides a compelling case of adaptation focused mainly, although not exclusively, on the introduction of coffee varieties that were new to local conditions in diverse territories. A significant number of different cultivars were developed in public and private institutions. Throughout Latin America, international organizations and government programmes have distributed these new cultivars with a varied reach. The Catimor cultivar lines were the main option for Latin American coffee farmers, given the high availability of these cultivars. Catimor lines are derived from the Hybrid of Timor, a natural cross between *C. arabica* and *C. canephora* (Bertrand et al., 2011).

A new hybrid line—the F1 Hybrids derived from crosses between wild Sudan-Ethiopian and American cultivars—has been obtained in Central America in the World Coffee Research Institute (WCRI) laboratories. F1 hybrids were developed in the Regional Breeding Programme (PROMECAFE), established in 1991 as an initiative of the Central American coffee institutes, CATIE in Costa Rica, and CIRAD. From genetic material of wild varieties from Sudan, Tanzania, Ethiopia and Kenya—obtained from the International Coffee Collection of CATIE, crosses were made with commercial varieties with coffee leaf rust resistance, such as Caturra, Catuai and Catimors and Sarchimors. After decades of field evaluation in trials in different environments in Costa Rica, Six hybrids were selected for their resistance to pests and diseases, good cup quality, high productivity, tall size, and good adaptability to different altitudes and agroforestry conditions. Of these, the hybrids “Centroamericano” (L13A44), “Milenio” (L12A28), “Esperanza” (L4A5), and “Casiopea” (L4A34) (the latter is susceptible to rust, but has excellent cup quality) were evaluated as suitable for Central America<sup>3</sup> [PROMECAFE (Programa Cooperativo de Mejoramiento Genético Regional para el desarrollo Tecnológico y Modernización de la Caficultura), 2003; interview with FM. Forest Seed Bank Unite of CATIE, 2 October 2019]. These new cultivars seem to cope well with environmental and climatic variability and offer more stable and increasing levels of productivity in shade-grown coffee while maintaining a quality

level similar to that of the traditional cultivars (Bertrand et al., 2011). To date, only Costa Rica, Nicaragua and Honduras have begun the distribution and commercialization of these F1s developed by the WCRI. In Mexico, their distribution is incipient.

The promise of coffee varieties tolerant or resistant to rust has created great expectations; however, the scale and depth to which their benefits are achieved could be hindered by a diverse set of factors that produce sub-optimal adaptive outcomes. Critical perspectives from the social sciences call for attention to be paid to how institutional structures of domination—political and economic—influence the distribution of resources such as access to information, knowledge, and funding (Eriksen et al., 2015). These critical approaches promote the notion of adaptation beyond the biophysical dimension and local sphere toward an interdisciplinary realm, where political ecology approaches and world-system perspectives and models of adaptation cycles can intertwine at different spatio-temporal scales (Gotts, 2007; Görg et al., 2017). They highlight the political nature of adaptation—a decision-making environment that reveals the contested character of the appropriation of nature—and the need to consider issues of power imbalance, exploring how environmental degradation at different scales reinforces structures of inequity and calling for the incorporation of political economy as a central object of analysis (Pelling et al., 2015).

These criticisms are pertinent in the light of the increasing number of cases of so-called *maladaptation*, a concept that is currently gaining ground (Dolšák and Prakash, 2018). It refers to the emergence of adverse consequences derived from adaptive actions that were initially implemented to improve a given situation (Barnett and O’Neill, 2010). The impact of these disruptive effects can be felt at different scales and can affect diverse social groups. The end result is an increase in the vulnerability of the system, even if some of its dimensions, e.g., local income, benefit in the short term. The extent to which a particular adaptive action can be labeled as maladaptation is difficult to determine. Different frameworks are being developed in order to systematically analyze a potential maladaptive outcome (Barnett and O’Neill, 2013; Magnan, 2014; Noble et al., 2014; Juhola et al., 2016). Despite its conceptual diversity, the notion of “maladaptation” warns against the risk of failing to consider adaptive planning and practice as a network featuring all kinds of scales, contexts, and contingencies.

The focus of this paper is not to determine whether or not the introduction of new coffee varieties constitutes a maladaptive practice; the multiple variables at stake and the wide range of subjectivities involved in our case study merits caution in terms of labeling this a case of maladaptation. The aspiration here is rather to identify how the potential for transformative adaptation becomes eroded in some aspects, while improving in others. This paper therefore adopts the concept of sustainable adaptation defined as “an adaptation that contributes to socially and environmentally sustainable development pathways, including both social-justice and environmental integrity” (Eriksen et al., 2011).

<sup>3</sup>These hybrids can only be reproduced vegetatively using the somatic embryogenesis technique, carried out in the laboratory, as they are crosses of two different parents. The possibilities of reproducing these hybrids under local conditions and maintaining their genetic purity are minimal.

## CASE STUDY

This paper describes exploratory and interdisciplinary research, designed as a case study<sup>4</sup> (Creswell, 2013). The making of statistical inferences is therefore neither its aim nor within its scope. A bounded system—two groups of small coffee farmers in the upper and middle part of the Tacaná Volcano coffee-growing area—has been designed in an attempt to understand the problems encountered in combating the effects of coffee leaf rust. A detailed geographical and sociological description of the study area is presented below:

### Study Area

The study area is located in the southeastern state of Chiapas, bordering to the north and west with the municipality of Motozintla, with the department of San Marcos in Guatemala to the east and with the municipality of Cacahoatán to the south. A specific study transect was established, producing a polygon of 177 km<sup>2</sup>, delimited by the following geographic coordinates: 15°12'67.54" N; -92°22'44.20" W; 15°01'77.32" N, -92°08'72.83" W (**Figure 1**).

The area of the quadrant includes the municipalities of Unión Juárez, Cacahoatán, and Tapachula. Economic activities in the area are limited to agriculture and commerce, coffee being the main crop and retail trade being the main commercial activity (INEGI, 2015). By 2013, 69% of the population was classified as highly socially marginalized, while 40% were placed at a medium level of social marginalization, indicating limited access to public services and structural deficiencies in housing conditions SEDESOL (2013).

The primary land covers and uses found within the quadrant include permanent rainfed agriculture (70.4%), secondary arboreal vegetation from the tropical montane cloud forest (10.7%), tropical montane cloud forest (9.16%), secondary bush vegetation from the tropical montane cloud forest (2.89%) and human settlements (2.7%) (INEGI, 2016). The elevational gradient of the study area, which rises from 30 to 3,500 masl, is oriented SW-NE. The predominant climates found along the elevational gradient are warm sub-humid, semi-warm humid, temperate humid, and semi-cold humid (INEGI, 2008). Precipitation exceeds 3,000 mm during the wet season, and ranges from 500 to 800 mm during the dry season (INEGI, 2008). The average annual temperature ranges from 15°C during the coldest months (November and December) to 34.5°C during the warmest months (April-May) (INEGI, 2008).

### Case Study Background

Environmental conditions at the higher elevations of the study area are ideal for the cultivation of high-altitude coffee (mainly Arabica varieties), which is appreciated by the market for its high cup quality. Areas of lower elevations, which are warmer and drier, usually feature cultivation of the Robusta type (*C. canephora*). There are 10,817 ha of coffee cultivation in the

studied quadrant. This area is distributed among 9,913 plots, corresponding to an average of 1.09 ha per plot. In the area, six polygons exceed 125 ha, reaching up to 290 ha (State Committee for Statistical and Geographic Information of the state of Chiapas, 2020). These correspond to large coffee plantations known as *fincas*, such as San Carlos, La Alianza, Vega de Los Gatos, Monte Perla, El Retiro, and El Zapote. Smaller coffee plots are the result of land expropriated and distributed during the twentieth century, most of which had previously formed part of larger coffee farms.

Coffee production in the area is predominantly family-owned, and generally hires workers from the community or other neighboring populations during harvest season, in which the coffee cherries need to be collected in the shortest time possible. Arabica coffee is mainly cultivated under the shade of trees of diverse use values; e.g., timber, fruit, or horticulture, among others. Robusta is also cultivated under the shade of trees, but with less dense shade. Arabica varieties are mainly processed into dry beans called “parchment coffee.” This procedure requires a precise fermentation process in which the pulp is removed, leaving the beans to then be sun-dried. Robusta type coffee does not require this pulping process, since, in most cases, the cherry is sold un-pulped or dehydrated. Robusta cultivation requires less labor during cultivation and processing; however, the bean price of Robusta can be up to 50% lower than that of Arabica.

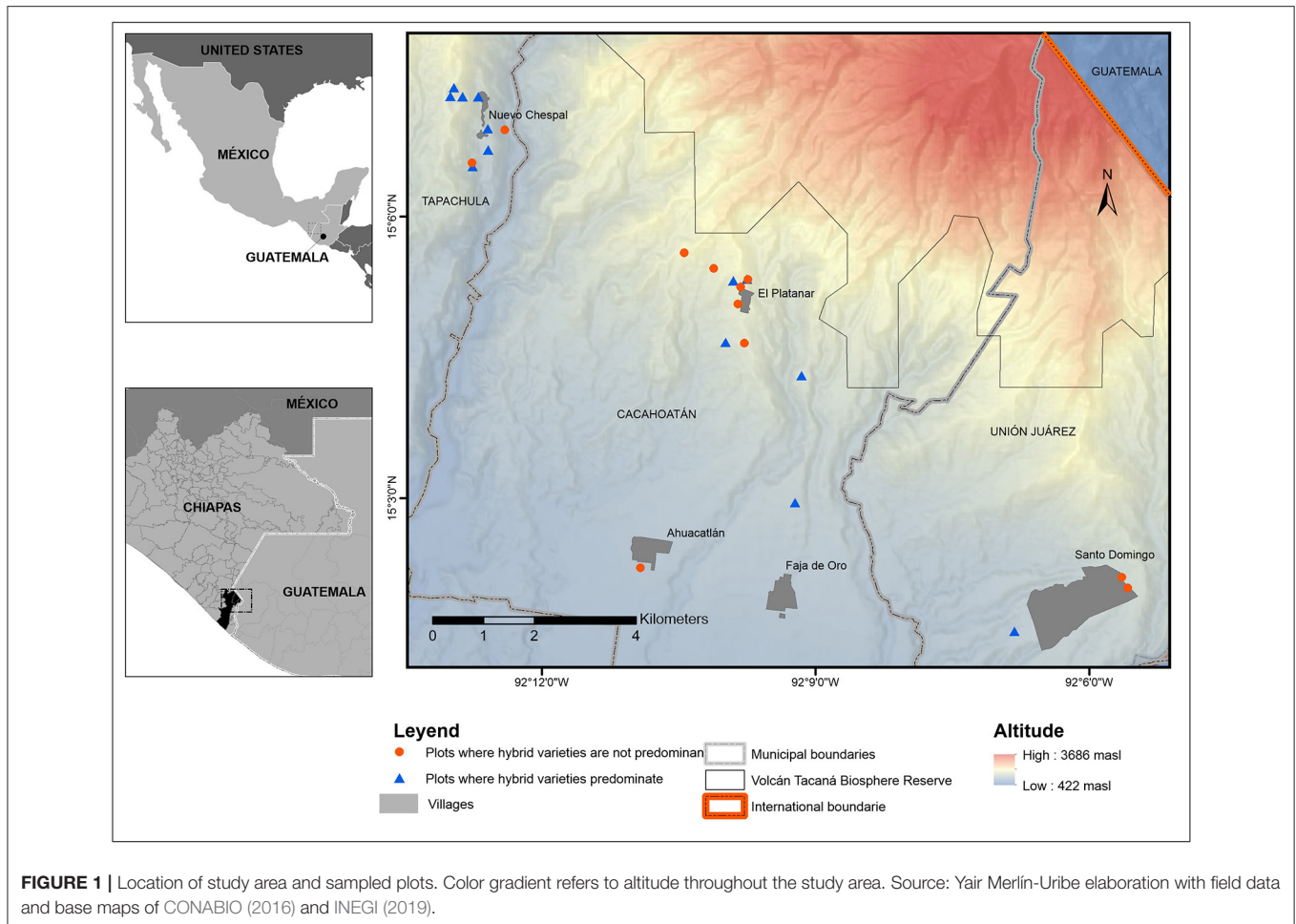
In the studied area, several coffee social organizations are working to provide various services for producers in exchange for an annual fee paid by coffee growers. Some of these organizations come from *Campesino* social mobilization. However, following the coffee leaf rust epidemic, entrepreneurial and even transnational organizations became important in the area through private coffee regeneration programmes. Of the total sample, 42% of the coffee farmers are permanently or intermittently affiliated to a coffee organization; of these, 36% were associated with the ISMAM Cooperative Society; 18% with Grapos S.C.; 9% belong to the organization Bosques de los Tordos A.C. and another 9% deliver their production to the company EGOS Café; and 9% pertaining to the local organization Bosques de los Tordos (9%) (see **Box 1** of **Supplementary Material**). Although they do not appear in the sample, there is also the intervention of non-governmental organizations, such as Heifer International, which has a coffee regeneration programme, with an important presence in the communities of Talquián and Córdoba Matanzas, in the municipality of Unión Juárez.

Social organic cooperatives, such as GRAPOS or ISMAN, offer technical advice. In the context of the coffee leaf rust epidemic, these organizations established links with the government's PROCAFÉ programme to manage the support of inputs and seedlings offered by the programme.

Membership of social organization maintains a strict adherence to different production protocols, including organic, 4C, Fair Trade or Rain Forest, among others. Coffee growers commit to selling their harvests completely or partially to the organizations, and thus the organizations establish financial commitments with marketers. Given that coffee is a very profitable product when purchased at a low price, there are independent buyers, known as *coyotes*, who buy coffee at

<sup>4</sup>“Case study research involves the study of an issue through exploration of one or more cases within a bounded system (i.e., a setting, a context) (...) involving multiple sources of information (e.g., observations, interviews, reports or surveys), and reports a case description and case-based themes” (Creswell, 2013, p. 73).





lower prices than those paid by the organizations. However, as documented by Milford (2014), selling to a *coyote* can be advantageous because payment is immediate, and purchases are made directly at the producers' homes. When selling to the organizations, the producers must transport the coffee to warehouses and payment can take up to 6 months, both of which can act to discourage selling the entire harvest to the organization.

The varieties traditionally cultivated in this area are Arabicas from the *Coffea arabica* species. Arabica varieties are considered *criollo* or traditional because of their historical permanence and presence in coffee plantations in the area. The oldest and more dominant at high altitudes are Typica and Bourbon (*criollo*) cultivars. These are appreciated by coffee growers because of their bean weight and low handling requirements. In the coffee market, these varieties are valued for their high quality, and are considered soft due to their low astringency and low caffeine content. Other varieties such as Maragogipe, Mundo Novo, or Caturra were later introduced in the area and are the result of a process of genetic improvement that took off in the middle of the twentieth century (Samper, 1999). With the Caturra variety, developed in Brazil in the 1970s, a process of modernization and modernization of the coffee plantation began, characterized

by the introduction of dwarf varieties, better adapted to sun conditions (Samper, 1999).

However, since 2014, these varieties, which are susceptible to coffee rust (*Hemileia vastatrix*) disease, have undergone gradual replacement by hybrid varieties (HV: Catimors and Sarchimors) that can be resistant or tolerant to certain strains caused by rust. Incorporating these new varieties not only solved the rust problem partially and temporarily, it promoted changes in survival strategies and in the landscape at the same time. Currently, most coffee plantations in the area present an indistinct mix of coffee varieties. Up to seven varieties can be found in a single plot, including Robusta. However, there is generally a predominant variety in this configuration, the dominance of which is determined by various factors that are either specific to the plot or influence decision-making during the coffee plantation renewal.

## Quantitative Sources of Information

A semi-structured questionnaire was designed with which to interview the population. The 73 questions explored themes of coffee plantation management, the impact of coffee leaf rust and the perception of the interviewees regarding environmental change. Prior to the field survey, the questionnaire was piloted

through informal interviews with coffee growers that were not included in the final sample. In March 2019, the coffee growers in the populations under study were invited to a meeting at which the objective of the research was explained and where volunteers were sought to answer the questionnaire and grant access to their coffee plantations for field sampling. Between March and April 2019, a total of 26 coffee growers were interviewed and the questionnaires filled out at the interviewees' homes or at their coffee plantations in a process that took between 20 and 30 min to complete. The interview sites and plot samples were georeferenced with a GPS application installed on a smartphone with an accuracy of  $\pm 3$  m. This information was subsequently verified and corrected with GIS software.

During the months of May and June, we sampled 26 coffee plantation plots. Sampling consisted of estimating the canopy cover within the coffee plantations, determining the type and percentage of soil cover and conducting a systematized soil sampling. The canopy cover variable was of interest in terms of investigating the effect of shade management, with the predominance of hybrid or arabica varieties. Similarly, soil cover is affected by canopy cover and can imply a need for intense management. Change in these two variables may indicate changes in the entire coffee plot. The smartphone application CanopyApp V. 1.0.4 (ORCI, 2018) was used to estimate canopy cover. This has been shown to have a similar sensitivity to a field densitometer, and has been used in other research (Davis et al., 2019). The application Canopeo V. 1.1.7 (Patrignani and Ochsner, 2015) was used to estimate soil cover. Using these applications, we recorded the vegetation cover percentages every 5 m in 25 spots within the 20 m<sup>2</sup> quadrant located in the center of the plot, and oriented in an east-west direction.

A change to high yielding varieties requires increased fertilization of the plantation. In this sense, we hypothesize that coffee plots where hybrid varieties predominate will have soils with higher fertility. To evaluate these changes, we focus on soil analysis. Soil sampling began at the center of each plot and followed a 20 m<sup>2</sup> quadrant scheme, in which five soil samples were collected at a depth of 20 cm: one at each of the quadrant's corners and one in the center. These five sub-samples were mixed to form a single compound sample representing the coffee plantation. This sample was then sent to a specialized soil laboratory to determine its basic fertility parameters. Soil analyses were conducted, following all of the parameters established by the Official Mexican Norm NOM-21-RECNAT-2000, at the Soil, Water and Plant Analysis Laboratory of the Faculty of Agricultural Sciences, Campus IV of the Autonomous University of Chiapas.

## Quantitative Data Analysis

The information produced by the interviews and field sampling was refined and standardized to meet criteria of validity, accuracy, completeness, consistency and uniformity (De Vaus, 2014). The data were processed for analysis using the Exploratory V. 5.3 and XLstat V. 2015 packages.

In order to identify management changes related to the varieties cultivated, the interviewees and their plots were split

into two groups based on hybrid variety (HV) predominance in their coffee plantations. Group 1 included producers that predominantly grew HV in their coffee plantations, while group 2 comprised producers that grew predominantly non-hybrid or traditional (*criollo*) varieties in their coffee plantations. Categorization of each participant was established based on their answer to one of the interview questions, which directly inquired about the dominant variety in their coffee plot. Subsequently, the genetic group of the variety was determined based on the World Coffee Research Catalog of Varieties (WCR, 2016).

To establish whether differences between groups were significant according to their probability distribution, hypothesis tests with an Alpha value of  $>0.05$  were used. For variables that met the criterion of normality, we used a bilateral *t*-test for independent samples with a 95% confidence interval. For those variables that did not meet the normality criteria, we used a bilateral Mann-Whitney test with a 95% confidence interval. We processed categorical variables using a Chi-square test with 500 Monte Carlo simulations, an *alpha* value of  $>0.05$  and one degree of freedom.

## Ethnographic Data

In order to contextualize the quantitative data, ethnographic data were used to record the subjectivity of the producers. In this way, we sought to provide a reading of the quantitative data that is sensitive to the specificities of the territory. Three sources of data were used: (1) 16 in-depth interviews with coffee producers<sup>5</sup> in different communities and one in-depth interview with a technician from an NGO that is delivering new coffee varieties in the area; (2) a workshop on replanting Arabica seedlings using a Robusta rootstock to avoid coffee leaf rust (attended by 12 coffee producers and conducted by a woman with expertise in coffee nurseries who currently works in one of the big private coffee plantations of the area, Community of Platanar, May 2019); and (3) informal conversations and field observations conducted over the period 2017–2019. All of this information was recorded in a field diary. Transcripts from the interviews were synthesized and thematically coded (Charmaz, 2006). For the purpose of this article, only issues related to the introduction of hybrid varieties are addressed: source of origin and availability of the new varieties, institutional support from the government program PROCAFE, seedling quality, problems encountered during substitution; growth difficulties and diseases of the new varieties; technical advice and assessment of the new varieties and producers' preferences and access to commercial channels.

## RESULTS

### General Characteristics of the Population

A total of 26 coffee producers were interviewed, and most of the interviewees were adult men. It was possible to confirm

<sup>5</sup>Interviews were conducted at different times between 2018 and 2019 (three interviews in the community of Chespal Nuevo; three in Aguacatlán, three in Santo Domingo, one in Platanar, three in Unión Juárez, and three in Talquián); interviews were mainly conducted in the plots of the coffee producers, but a few were held in their homes; only three of the interviewees were women.

that, even after a fall in productivity caused by coffee leaf rust and climatic phenomena, coffee cultivation continued to be the main occupation of the interviewed population. Despite the fact that migration is a deeply rooted process in the area, most interviewees remained in the community working on the coffee plantations. However, almost a third of the interviewees reported having at least one precedent of migration in their lives. The proportion of households receiving remittances was slightly over a third. For the rest of the sample, the main sources of economic income were coffee sales, some commercial retail activity, or employment as agricultural laborers in the area's coffee plantations or in other crops grown in municipalities at a lower elevation. Little governmental support was received, with just over a third of the population benefiting from social programs.

Coffee production was considered small-scale, given the limited area under cultivation and number of plots. During the process of selecting varieties with which to renew the coffee plantation, half of the producers adopted hybrid varieties. In comparison to other regions in the state, membership of coffee organizations was low, with less than half of the growers associated with any organizations. These were mainly associated with organizations with organic and 4C certifications. The data also reveals that almost all coffee growers had been affected by coffee rust in recent years (Table 1).

### Characterization of Coffee Plots Sampled

The sampled coffee plots were located at an average altitude of 1091 masl. Most of the coffee plantations were located in mountainous areas with slopes of over 50%. The average area of the plots was 2.6 ha. Considering that the average distance between coffee bushes was 1.7 m, the average planting density was estimated at 3,460 bushes per ha. The average shade coverage over the coffee bushes was 48%. The predominant soil cover of the coffee plantations was leaf litter with an average cover of 50%. Weed vegetation covered an average of 30% of the coffee plantation soil. The average number of years of coffee cultivation on the plots was 21 years, while the average number of years of ownership was 27 years, indicating that most of the owners have cultivated coffee on their plots since they acquired or inherited them (Table 2). Tenure was under *ejido* communal ownership and coffee farmers had to abide by the normative standards of the *ejido*.

### Predominance of New Varieties in Coffee Plots, Sources of Distribution, and Technical Assistance

Most of the plots sampled were inherited, so plantation age varied greatly. One of the plots had cultivated coffee for 90 years, while the most recent plot was a 3-year-old plantation. The average age of coffee plots was 21.5 years. Prior to regeneration, most of the coffee plantations grew Arabica varieties, mainly Typica, Bourbon, and Maragogipe; however, after 2012, these traditional varieties were substituted because of the defoliating effect of the coffee rust. Arabica varieties, in general, were partially or gradually discarded. Just over half of the coffee growers introduced a variety that they identified as improved, resistant or tolerant to rust. Thus, in half of the coffee plots surveyed,

hybrid or Robusta varieties currently predominate, while Arabica traditional varieties dominate the rest. A third of interviewees identified government entities as donors of coffee plants used during the substitution process; the rest bought their plants or received them as donations, mostly from coffee organizations.

Technical assistance during regenerations was scarce. Those who received it stated that it came mainly from technical personnel sent by organizations or by government technicians. The rest carried out their regenerations by following the cultural practices of the area or by taking advice from other coffee growers. Although the introduction of hybrid varieties required modifications to be made to the coffee plantation management, the majority of growers failed to do this. Only a few made some small changes when managing the new varieties. Overall, they continued to manage the coffee plantation in the same manner as they had done in the past (Table 3).

### Quality Perception of Varieties Used

In general, the varieties used for substitution were perceived as being of medium quality, especially when compared with the traditional Arabicas. This was primarily due to low bean yield; i.e., more coffee cherries were required per kilogram of parchment coffee. Several interviewees mentioned that the Catimors produce a higher proportion of incompletely developed beans or "vain beans," which reduces the coffee growers' income since more work is necessary to harvest the fruit and the harvest proportion is smaller. On the other hand, despite successive outbreaks of coffee rust and a perceived increase in pests and diseases, only a little more than half of the coffee growers applied some type of pest or disease control to the new varieties. This lack of pest control is detrimental to the physical quality of the coffee beans. Overall, the population employed a total of 16 varieties with which to renovate their coffee plantations. The Catimors were among the most popular of these varieties, but had the worst reputation in terms of quality and bean yield. Catimors and Sarchimors were the dominant lines distributed *via* the government program PROCAFE (Table 4).

### New Varieties, New Management?

The introduction of new coffee varieties requires changes to be made in coffee plantation management. However, comparative analyses between the groups showed that, overall, there were no significant differences between the management variables analyzed. Only the percentage of bare soil in the coffee plot and percentage of affiliation to coffee organizations presented a statistically significant difference. The percentage of bare soil was higher in the plots where the hybrid varieties predominated, which may indicate changes in shade management, since the interviewees reported that the Catimors required more sunlight than the Arabica varieties. Some growers made changes in their management, especially those who received technical advice, but these changes were not permanent and were manifested only during the first year after regeneration (Table 5). The majority of the growers regressed to their traditional management even though hybrid varieties were now predominant in their coffee plantations. On the other hand, coffee quality is a determining factor for the success of coffee organizations, which explains why



producers belonging to a coffee organization gave priority to the cultivation of Arabica varieties. Statistical tests did not detect significant differences between groups in terms of the shade cover in their coffee plantations. The plantations with less shade coincided with those managed more intensively, or those with Robusta or hybrid variety predominance. However, these were observations made during field visits to the area (Table 6).

Comparing these management variables before and after introducing new varieties did not reveal significant differences, except for the variable of soil conservation practices, where it was possible to confirm that there had been a slight increase in these practices in both groups of coffee farmers. This increase in soil conservation practices is possibly related to the removal of shade and exposure of the soil to climatic factors that are intensified without the protective foliage of the shade trees. In the interviews, it was reported that the strong changes in coffee plantation management occurred mainly during the first year of the introduction of the new varieties, since coffee plants are very dependent on light and humidity levels. There was a set of management practices that most of the interviewees conducted on a regular basis, such as herbaceous plant and shade management, ditching and pruning of the coffee plants. Other practices that were only carried out by a very low proportion of the interviewees included pest management, chemical fertilization or composting, all of which are determinant for the production and health of the coffee plant. Failure to carry out these practices seriously compromises the sustainable production of coffee, whether cultivating arabica or hybrid varieties (Figure 2).

## ADAPTATION BETWEEN PRODUCTIVITY AND AGROFORESTRY BENEFITS: COMPLEMENTING QUANTITATIVE DATA WITH READINGS FROM ETHNOGRAPHIC DATA

The coffee growing area of the Tacaná Volcano has passed several historical milestones in the production of coffee. From their beginnings in the 1880s to the present, the Tacaná coffee plantations have experienced the golden age of support from the Mexican Coffee Institute in the 1980s, the end of the production quota system and the international coffee crisis in the 1990s, the effects of Hurricane Stan in 2005, the latest and most aggressive coffee rust epidemic in 2013 and then the impact of the 2016 earthquake and the growing influence of climate variability, to mention the most prominent of these milestones. The present times are characterized by the facing of a crossroads between productivity and producing coffee in a sustainable and environmentally friendly way, while maintaining the environmental benefits of agroforestry systems. Biotechnology, with its latest developments in the genetics of coffee hybrid varieties, plays a fundamental but as yet undefined role in this dilemma. New coffee varieties have the potential to bring together the two paths, productivity and high quality beans, in agroforestry systems. How is the process of introducing new

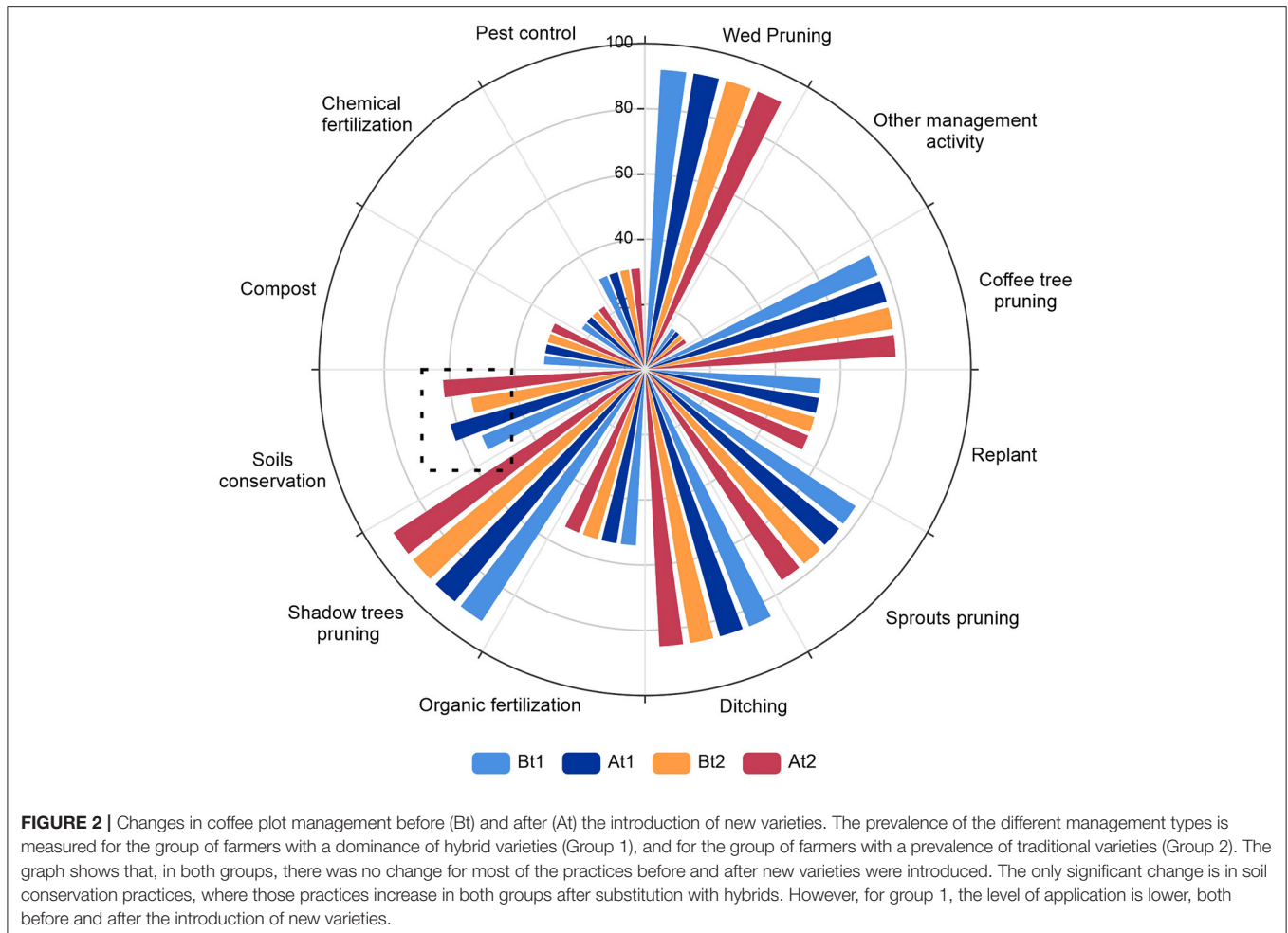
coffee varieties in this area unfolding? And what implications are emerging from an adaptation point of view?

## Origin and Availability of Coffee Seedlings for Replanting

In the wake of the coffee leaf rust explosion in 2013, a growing and irregular flow of new fungus-tolerant coffee varieties emerged from different origins. Different public and private actors have engaged in the task of obtaining hybrid seed and producing it in technified nurseries. However, the main supply of seed comes from the federal programme PROCAFE, which has launched a process of replacing traditional varieties with new hybrid varieties. PROCAFE sought to regenerate the old and exhausted coffee plantations in many areas of Mexico. For our case study, the age range of the coffee plantations is wide, with an average of 21 years (see Table 3), but comments regarding how the parents and even grandparents of the current coffee farmers established the coffee plantation are commonly made in interviews and informal conversations (see Ruiz de Oña, 2018). Therefore, coffee leaf rust occurred in old coffee plantations that had made little investment in management due to falling coffee prices, and even swept through coffee plantations located at elevations where the disease had never previously been seen (field observations and informal conversations in Unión Juárez and Talquián). Despite the low productivity of coffee plantations—even before the impact of coffee leaf rust, the main incentive to introduce new coffee varieties was the rust (see Tables 1, 3).

With PROCAFE, a process of seed and seedling distribution initiated, which led to a remarkable genetic dispersion. Exchange of seeds, reproduction of these new varieties in uncontrolled conditions in backyard seedbeds and mixing with other tolerant varieties obtained by various means—acquaintances, friends, local nurseries—are common practices on both sides of the Tacaná border. This flow and dispersal is due, in principle, to the limited distribution of seeds from PROCAFE, restricted to those farmers registered in the SAGARPA (Ministry of Agriculture and Fisheries of the federal government) census. For our study, only one third of the coffee farmers received seedlings from PROCAFE, and in quantities far below those promised by the programme (most coffee farmers claim to have received about 300 seedlings, when the programme promised 1,000 plants and both of these figures represent insufficient quantities for a complete regeneration of the plot). On the other hand, the group of farmers with a predominance of new varieties presented less affiliation to organizations (statistically significant difference) and less support from the government, in terms of receiving seedlings and technical assistance (see Table 3). Those who did not receive support from the government program sought alternative sources of supply for their seedlings. These were obtained either formally, through purchases or as donations from NGOs operating in the area, or informally, through family members and friends on both the Mexican and Guatemalan side of the border. In the latter country, it is possible to find hybrid plant production in backyards and farms, with and without certification (Ruiz de Oña, 2018). One of the possible implications of this gene flow, uncertified and without control





procedures, is the loss of rust resistance in successive generations of the newly introduced varieties.

### Problems Encountered During Substitution by New Hybrid Varieties and Coffee Farmers' Subjective Assessment of the New Varieties

In principle, the new plants offer high productivity and resistance to coffee leaf rust, but 32% of the farmers considered them to present low productivity (see **Table 4**). Many of the grains were low in weight and did not ripen; hence, they had a higher proportion of “empty” grains than crops with traditional varieties (see section Quality Perception of Varieties Used).

In several cases, the quality of the delivered seedlings was also sub-optimal. Several coffee farmers reported receiving seedlings already affected by nematodes and other diseases (Ruiz de Oña et al., 2019). Hence, it was not uncommon to observe seedlings growing with little physical vigor. Compared to the new varieties, there was a general preference for the aroma, weight, color, and taste of the traditional varieties. However, the higher susceptibility to coffee leaf rust and the old age of the coffee

plants compelled the coffee grower to substitute these for the new varieties.

### Consequences of the Lack of Modification to Management for the New Coffee Varieties

In addition to the dubious quality of the seedlings delivered, the lack of adjustments to the agronomic management undermined the productive and adaptive potential of the new varieties. These newly introduced varieties, mainly Sarchimors and Catimors, are more demanding in terms of management and input than traditional varieties, especially during the early years of their development. A significant percentage of the farmers interviewed consider that the new varieties require more fertilizers and care than traditional varieties (**Table 6**). In relation to this issue, there were no statistically significant differences between the group with no predominance of new varieties and the group with a higher prevalence of new varieties. In the latter group, however, with more experience in the care of hybrid varieties, up to 53% of growers consider that these varieties require more intensive management (**Table 6**). Our data confirm that this management

**TABLE 1** | Characteristics of the population under study ( $n = 26$ ) Yair Merlín-Uribe elaboration.

	Frequency (%)	Mean (min–max)
Producer's age (years)	–	57.4 (31–79) $\pm$ 12.35
Male sex	85	–
Coffee cultivation is main occupation	80	–
Immigration background	35	–
Reception of remittances	35	–
Social program beneficiary	39	–
Number of plots	–	2.2 (1–7) $\pm$ 1.38
Cultivated area (Ha)	–	2.7 (0.3–5.75) $\pm$ 1.48
Grows mainly hybrid varieties	53	–
Membership of a coffee organization	43	–
Certification of the plot	30	–
Recent affectation by rust	92	–

**TABLE 2** | Main characteristics of the sampled coffee plantations ( $n = 26$ ) Yair Merlín-Uribe elaboration.

Feature	Average	Min–Max	Standard deviation
Plot elevation (masl)	1091.1	(669–1,403)	$\pm$ 225.2
Terrain slope (%)	47.0	(3–87)	$\pm$ 25.4
Crop area (ha)	2.7	(0.3–5.8)	$\pm$ 1.5
Distance between coffee bushes (m)	1.7	(1–4)	$\pm$ 0.6
Shade coverage (%)	48.2	(9.2–78)	$\pm$ 20.8
Age of coffee plantation (years)	21.2	(3–90)	$\pm$ 21.5
Land tenure (years)	27.5	(2–80)	$\pm$ 25.5
Arabica and Robusta coffee yield (t/ha)	1.3	(0–8)	$\pm$ 1.8

adjustment did not take place in the hybrid-predominant group; the farmers continued to manage the new plants in the same way and with the same intensity as the traditional varieties. Resources invested in coffee cropping were just sufficient to obtain a minimum yield, while at the same time reducing the impacts of coffee leaf rust.

This result was due to a combination of contextual factors related to the coffee grower's economic conditions along with the manner in which seedlings were distributed. In a context of financial scarcity and high risk in the commercialization of the product caused by falling prices and high levels of market volatility and unstable trade channels (Sach et al., 2019), the average coffee grower applied a strategy that prioritized cost reduction and risk minimization (Hansen et al., 2007). Coffee growers were confident of achieving a stable production by simply introducing new varieties without making any of the major changes associated with them.

As a consequence, substitution was unsystematic. The growers mixed traditional varieties with hybrids in the same plot. In many cases, this was carried out with no knowledge of which varieties they were planting and without taking into account the seed's certification, which guarantees its tolerance to rust.

**TABLE 3** | Characteristics of the coffee plantation regeneration ( $n = 26$ ).

	Frequency (%)	Mean (min–max plot)
Elevation (masl)	–	1091.1 (669–1403) $\pm$ 225.16
Average age of the coffee (years)	–	21.2 (3–90) $\pm$ 21.49
Previous Arabica variety	80	–
Recent regeneration of the coffee plantation	100	–
New varieties introduced after 2012	84	–
Substitution with new varieties due to rust	73	–
Substitution with hybrid varieties	53	–
Predominance of new coffee varieties in coffee plantations	50	–
Plants donated by the government	30	–
Receiving technical assistance at the stakeout	24	–
Receipt of supplies from the government	24	–
Modification of the management of the coffee plantation	43	–

*The renewal was mainly focused on the Arabica varieties due to the damage incurred by coffee rust. Yair Merlín-Uribe elaboration.*

**TABLE 4** | Characteristics of new varieties replanted ( $n = 26$ ).

	Frequency (%)	Count
Regular quality of the replanted variety	80	
Low grain yield	32	
Controls rust	58	
Catimor is dominant variety	43	
Total number of varieties used	–	16

*Grain quality of the introduced hybrids, especially Catimors, was regular. Yair Merlín-Uribe elaboration.*

This served to complicate the differentiation of management according to variety.

## Low-Medium Grain Quality and Implications for Obtaining Trading Opportunities

As a result of this disorderly and confusing hybrid-introduction process, the average coffee grower suffered a loss in bean quality (see **Table 4**). This led the grower to offer the harvest even cheaper and to sell to the highest bidder, often to the “*coyotes*” who are prominent in the area, sometimes acting as independent intermediaries or as subcontractors for the large coffee-roasting companies. Bean quality, a possible gateway to better-paid market niches such as speciality coffees, is depressed by the *coyotes* throughout this process.

The *coyote* collects and mixes the grains produced in the area without classifying them by quality and variety. Production conditions and procedures in the selection of grain are thus increasingly tailored to coffee roasting companies, the main business of which is the production of instant coffee, with

**TABLE 5** | Agronomic characteristics in coffee plantations according to variety dominance in plantations.

	Hybrids are not predominant (n = 13)	Hybrids are predominant (n = 13)	Test statistics
Distance between coffee plants (m)	1.73 (1–2.5) ± 0.41a	1.59 (1–4) ± 0.78a	U = 46 P ≤ 0.12
Number of plots (count)	2.62 (1–7) ± 1.71a	1.69 (1–4) ± 0.85a	U = 45. P ≤ 0.11
Arabica parchment coffee yield (t/ha)	0.41 (0–1.6) ± 0.46a	1.57 (0.04–8.05) ± 2.23a	U = 94 P ≤ 0.20
Arabica and Robusta coffee yield (t/ha)	0.97 (0.00–5.33) ± 1.51a	1.79 (0.04–8.5) ± 2.18a	U = 89.5. P ≤ 0.31
Price per quintal of Arabica (\$)	1749 (977–3000) ± 993.32a	1988 (977.5–2800) ± 534.31a	t = 0.75 P ≤ 0.46
Age of renewal coffee plants	4.69 (1–21) ± 5.23a	3.69 (2–7) ± 1.75a	U = 0.77 P ≤ 0.77
Canopy cover (%)	49.14 (70.9–22.2) ± 17.11a	50.46 (12.6–76) ± 20.8a	t = 0.16 P ≤ 0.87
Bare soil (%)	11.64 (4–20) ± 4.88a	16.31 (8–28) ± 5.76b	t = 2.12 P ≤ 0.05
Total nitrogen (%)	0.08 (0.01–0.14) ± 0.04a	0.11 (0.01–0.31) ± 0.08a	t = 1.06 P ≤ 0.30
Potassium (mg/kg)	53.67 (23.5–112.6) ± 25.48a	111.8 (22.3–327.2) ± 94.78a	U = 97 P ≤ 0.15
Organic matter	7.60 (4.20–12.10) ± 2.33a	9.99 (17.20–6.10) ± 3.91a	t = 1.77 P ≤ 0.09
Phosphorus (mg/kg)	8.05 (1.9–27.7) ± 7.22a	5.83 (1.35–17.30) ± 18.85a	U = 54.5 P ≤ 0.34

Plots with a dominance of new varieties had a greater percentage of bare soil. Yair Merlín-Urbe elaboration.

The different letters in each column denote significant differences according to the Mann-Whitney/bilateral ( $P < 0.05$ ) and bilateral student t test at  $P < 0.05$ .

**TABLE 6** | Management characteristics according to variety dominance within the coffee plantation.

	Hybrids are not predominant (n = 13) frequency (%)	Hybrids are predominant (n = 13) frequency (%)
Affiliation with a coffee organization	61.5a	23.0b
Beneficiary of social programs	30.7a	46.1a
Plants donated by the government	38.4a	23.0a
Hybrid varieties require more work	30.7a	53.8a
Shade removal	84.6a	61.5a
Received technical assistance	38.4a	7.6a

The HV were predominant in the coffee growers' plots that were not associated with any coffee organization. For the rest of the variables, no significant association was found. Yair Merlín-Urbe elaboration.

Frequency followed by a different letter differs significantly according to the Chi-square test. The d difference is significant at  $P < 0.05$ .

little regard for quality. The chances of entering the alternative markets with greater added value of such speciality coffees thus become narrower. In the study area, in contrast to other areas of Chiapas, there is a predominant commercial context that does not encourage quality production, even if the coffee produced in the area, especially in the higher parts, is of consistently good quality. This is not a characteristic that is rewarded economically and thus the motivation for high quality grain declines with the next harvest. This, however, also has negative implications for the coffee farmer, since the amount of grain discarded by *coyotes* increases. Coffee farmers in the study—together with many others who, over the course of 3 years of fieldwork, share their thoughts and experiences—complain and express their dissatisfaction in different forums and workshops. Specifically, the coffee growers demanded the return of the amount of beans that the *coyote* discarded as unmarketable and discounted when paying for the delivered harvest.

With the introduction of the new varieties and their dubious bean quality (see section Quality Perception of Varieties Used), the balance toward a lower quality coffee is reinforced, exacerbating the problems of coffee commercialization.

## Institutional Support and the Link to the Coffee Organizations: Implications in an Unstable Organizational Environment

Management of new hybrid varieties was not reinforced through resources and knowledge devoted to the improvement of production of high-quality coffee under agroforestry conditions, and the coffee growers who belonged to a production organization did not receive higher degrees of technical assistance. The organizational factor and organic certification, which are sources of commercial strength and better quality information elsewhere, did not seem to fulfill this function in our study area. Technical advice and PROCAFE's support was mainly managed and distributed by service providers authorized by the Mexican Ministry of Agriculture, who formed *ad hoc* organizations to receive funding, inputs and sometimes to produce the plants.

In this area, we observed a weakening of the historical organizational forces in their many forms (cooperative societies, traditional trade unions and campesino organizations and communal Mexican *ejido* assemblies) (Merlín-Urbe et al., 2018). (See supplementary documentation, **Box 1**, for a brief description of the organizations that provided coffee seedlings to the sampled farmers). The working groups were coordinated under the professional service provider—private and technically oriented, with no political component—sharing the stage with traditional organizations but differing significantly in their mode of operation. Technical organizations formed under PROCAFE were able to attract dissatisfied members of traditional campesino organizations, or non-affiliated coffee farmers, into their ranks. However, their presence was occasional and limited to the management of the government program with inputs and plants.

## Implications of Current Policies for Regeneration With New Varieties

Our data questions the wisdom of adopting coffee regeneration strategies that promote or prioritize high yields at the risk of compromising the cup quality of the coffee. Currently, this quality of product is precisely what the international market rewards. According to Pérez-Akaki and Echánove Huacuja (2006), in the current context of liberalization and deregulation, the five large foreign companies that control the collection and commercialization of coffee in the region establish not only the price, but also the quality standards of the grain. The size and quality of the bean are evaluated by these companies, and they are thus the yardstick by which the social sector's coffee production is measured, and there is often punishment where it fails to meet these standards.

Policies promoting increased production, but of a lower quality coffee, cast doubts on CAFS's long-term capacity for adaptation. Instead, policy alternatives that foster the production of high-quality coffee beans in shade-grown coffee fields would, in principle, help access better prices (Bertrand et al., 2011). This could, in turn, also have important implications for environmental sustainability.

## Erosion of Ecosystem-Based Adaptation

Most of the coffee plots are distributed over mountainous terrain, with significant slopes (landslides are common in the area, as are earthquakes). They are immersed in a matrix of forest, suffering the constant presence of animals, such as moles, which erode the soil and damage the roots of the coffee plants. Many of the plots present an accumulation of water and humidity, as there are several surface and underground streams that surround the coffee plots, while weeds and trees for firewood and fruit are scattered among the rows of coffee plants. All of this forms an agroforestry system with many uncontrolled variables, where the functional and structural diversity of the system is high. Traditional varieties, such as *Typica* or *Bourbon*, were adapted to this rugged terrain. However, the new varieties require less aggressive and more controlled growing conditions, with more intensive fertilizer and pesticide management. They perform best with low levels of shade and even in full sunlight.

Regarding shade management, although there are no significant differences in shade cover between the two groups of coffee plots (Table 6), there is an observed tendency to intensify the pruning of shade trees, following technical advice in the area. There are even a few cases of complete suppression of shade. Maintaining an adequate percentage of shade on coffee plantations is crucial for coffee productivity and quality (Soto-Pinto et al., 2002), but shade also fulfills other functions that are seldom considered when the management of coffee intensifies. These include the provision of fruit or timber, which interferes with the decision to carry out hard pruning in order to lower the density of foliage.

Several farmers report damage to the plants due to heavy rainfall in the off-season as a consequence of increased climatic variability. These atypical and irregular rains coincide with the coffee cleaning and shade pruning season between February and March, which is normally a dry season. In several of the

plots surveyed, farmers showed increased soil erosion problems due to reduced shade protection. The trend toward reducing forest cover acts to diminish the adaptive ecosystem dimension, originally the main focus of adaptation practice (Akamani and Holzmueller, 2017).

Despite the limited nature of the technical assistance (see section Predominance of New Varieties in Coffee Plots, Sources of Distribution and Technical Assistance and Table 6), it seems to have had some influence on shade reduction. The farmers claimed to follow the technician's indications when asked about the reason for reducing the shade cover. In some cases, especially among older farmers, this advice is not well-received. In others, the recommendation to maintain 40–45% cover, a level well-known to the farmer, may be interpreted as an invitation to open the shade further. Finally, in the search for higher yields, many coffee growers look toward large private farms, where there is a clear tendency to cultivate coffee under sunlight.

Introduction of new genetic material from the new varieties can be seen as a way to increase the narrow genetic diversity of Arabica traditional cultivars (Bertrand et al., 2011; Aerts et al., 2017). However, this trend does not compensate for the erosion of structural and functional diversity in CAFS. There is an ongoing process of landscape simplification and homogenization seeking to achieve higher productivity. The implications of this in terms of adaptation are clear: the way in which the new varieties are being introduced does little to strengthen the adaptive properties of the agroforestry systems (Cerdeira et al., 2020).

## The Growing Popularity of Robusta Coffee: An Alternative Pathway of Adaptation?

The results indicate an expansion of the Robusta species along an altitudinal gradient. Since the 1980s, Robusta has dominated on the lower and middle slopes. Its presence at higher altitudes is beginning to be noticeable. We have observed plots of Robusta coffee in the community of Unión Juárez at 1,250 m. where it is beginning to compete seriously with Arabica. Only 10 years ago, this was a community that grew only Arabica cultivars, because Robusta did not thrive at such altitude and fresher temperatures. Today, it is growing without problems. We have also seen plots of Robusta at altitudes up to 1600 m., in the community of Córdoba Matanzas. At this altitude, it is the hybrid Robusta that thrives, but not the traditional Robusta.

We argue that this displacement is primarily due to the increasing climatic variability that allows the establishment of Robusta where it could not grow before. In addition to this, The Nestlé Company (with a long time presence in the lower parts of the Tacaná) is promoting a hybrid Robusta cultivation in high altitude communities (Nestlé presentation at the Casa Ejidal in the Community of Unión Juárez, 15th of October 2017).

In the context of the coffee leaf rust epidemic and with higher climatic variability, the presence of Nestlé and its promotion of hybrid Robusta finds the perfect conditions for its expansion. However, several coffee growers have told us about diseases and pests in Robusta as well. It may not be coffee leaf rust, but Robusta cultivars are not free of problems.



There is, however, a counterbalance to this expansion: the newly introduced dwarfed hybrid varieties are also being planted in low-medium altitude communities where Robusta has long been dominant, and where traditional tall varieties such as *Typica* and Bourbon have long been out of cultivation due to the high incidence of coffee leaf rust at lower altitudes.

### Taking Stock of the Regeneration Process and the Performance of New Varieties: Adaptive Implications

The evidence presented here points to contradictory findings in terms of long-term sustainable and equitable adaptation. In our case study, the cumulative effects expected after the introduction of new varieties was limited by management factors interacting with the prevailing economic and political conditions. The coffee farmers' adaptive response, initially of an incremental nature, ultimately became a limited coping adaptive practice.

The degree of adaptation shown in this process can therefore be considered regressive: it strengthens the previous dynamics of the socio-environmental system that were a source of social, economic and environmental vulnerability. The transformative potential in an initially incremental adaptive practice is eliminated, not only in terms of the dimension of production.

In summary, the regeneration process triggered by coffee leaf rust is adjusted to the prevailing political and economic conditions in the coffee cropping system. These conditions, however, are not aligned to the promotion of agroforestry features with a long-term adaptive character. In the face of increasing climate variability in the medium and long-term, this reduction in ecosystem adaptation constitutes a source of new vulnerabilities.

## DISCUSSION AND FINAL REMARKS

Our case study demonstrates that the expected productivity increase is not aligned with promoting agroforestry features with a long-term adaptive character. The new varieties require significant fertilizer inputs, together with pesticide application. They also thrive better in coffee systems under sunlight than in agroforestry conditions with medium to high levels of shade and functional and structural diversity. The ruggedness of the terrain and the economic precariousness of the coffee growers—affected not only by rust and the consequent decline in harvests over recent years but also by the vagaries of the international market, which punishes them with prices below production costs—worked against the optimal development of these varieties. The necessary management changes were only partially implemented, partly because of financial constraints. The shade reduction and higher input application (by the coffee farmers who could afford it) to guarantee the survival of the new seedlings and achieve the promise of high productivity levels ultimately caused other problems, including soil erosion due to heavy and irregular precipitation.

The economic conditions were not suitable for upgrading the management of the varieties, and the coffee plantation regeneration strategy implemented by the government's

PROCAFE programme fell short of acknowledging so. PROCAFE was focused on producing seedlings in nurseries and distributing the new varieties (see Ruiz de Oña et al., 2019 for a detailed description of PROCAFE's performance in the area); however, the varieties selected for replanting, the quantities distributed among organized groups of coffee farmers and the inputs promised to support optimal plant growth were all inadequate. Numerous administrative irregularities, mistrust among the coffee farmers along with a lack of information and technical advice that focused on intensifying the system rather than on conserving the agroforestry features, combined to push the coffee system toward new imbalances. All of these factors acted to reinforce the trend toward a reduction in the diversity of the agroforestry system. According to Akamani (2016) and Harvey et al. (2018), adaptive capacity is eroded as the system becomes simplified and its diversity reduced. In the face of climate variability, erosion of ecosystem adaptation acts as a source of new vulnerabilities (Nalau and Becken, 2018).

Introduction of the new varieties allowed coffee yields to recover. However, the lower quality of the beans and failure to adjust the management to the production requirements (no major changes in management practices were evident among the group with a predominance of new varieties) did not improve crop quality. The producer faces a dilemma: obtaining higher productivity to compensate for low bean quality but without the sufficient means to guarantee high performance of the new coffee varieties. Then, when the new varieties are to be commercialized, the buyer discards a significant portion of the grain due to low weight and physical defects; in many cases, the producer also loses out on the premium price for quality. In the case of organic producers (Talquán for example, in the GRAPOS Cooperative), application of inorganic fertilizer to boost growth of the new varieties meant that they lost the premium for growing their coffee organically. In turn, the increased susceptibility of the new varieties to other diseases such as rooster's eye, together with low fertilizer application, also contributed to irregular growth and plant weakness in a form of positive feedback that reproduced and amplified vulnerability.

Quantitative analysis of agroforestry elements such as soil cover, shade cover, and coffee management, and qualitative analysis of commercialization and quality of the harvest, indicate a limited adaptation outcome: avoiding coffee leaf rust affectation did not lead to an adaptive response that tackles both sustainable and high-quality production. The exclusive focus on productivity by any means acts to jeopardize the latter. Adaptation led to reactive and autonomous responses to cover the shortcomings of the government program and the limited capacity of the majority of the coffee growers to achieve a sufficient level of investment to guarantee the successful management of the new varieties.

The case study reveals how political structures and economic conditions influence adaptation pathways and outcomes. The benefits attributed to the new varieties in our case study were limited or reversed by institutional rigidity (Allison and Hobbs, 2004; Gotts, 2007) and inefficient patterns of governance. This shows how political mechanisms aiming to foster coffee productivity act to constrain the producers' agency while

increasing their dependence on external factors that are difficult to control. The political nature of adaptation becomes evident.

Current adaptation options in terms of land management, knowledge dissemination, institutional regimes, and economic conditions of production appear to be reproducing values and production modes that reinforce a continuity scenario: one that implies increasing levels of risk and uncertainty in coffee agroforestry.

The study also shows the potential risk of maladaptation trends by introducing an adaptive strategy without the necessary means to support the transition to a changing state. Short-sighted adaptation ends up disrupting socio-environmental relationships in such a way that the path toward transformative adaptation closes. The importance of designing more comprehensive adaptation strategies that address the interconnectedness of vulnerabilities (Eriksen et al., 2011) and increase the chances of transformative adaptation (Verburg et al., 2019) is evident from our case study.

The *Campeño* smallholders of the Tacaná lived through the times when the Mexican Coffee Institute (INMECAFE) managed the production of coffee beans with inputs, credits and mechanisms for collection and commercialization in an international market that, until 1989, was heavily regulated. Afterwards, they would experience the international coffee crisis and the collapse of the trade regime under the tutelage of the Mexican State (Renard, 2010). Finally, within the framework of neoliberal deregulation policies, they would see the fall of coffee prices at the hands of a highly deregulated market under neoliberal economic theory (Topik et al., 2010). Abandonment and migration coexisted with the disincentive to cultivation. Today, this legacy is reinforced in the context of climate change. The coffee leaf rust epidemic of 2013 hit a type of coffee plantation that had gone through a first wave of modernization, only to pass into a state of slowing intensification, a kind of truncated modernity, which left the coffee landscape with significant signs of degradation.

The coffee rust epidemic came to stimulate a second wave of modernization, but this time in a different context: high climatic variability, increased disease and pest affectations, high market volatility, reduced government support, scarcity of credit. These features coexist with the organic turn, the sustainability discourse, the promotion of the benefits of agroforestry systems from bodies dedicated to genetic improvement such as World Coffee Research, and a new process of genetic renewal.

This second wave of productive intensification is once again unfinished or partially developed. It exhibits similar characteristics to the first wave of intensification under INMECAFE (introduction of dwarf varieties, reduction of shade, increased use of agrochemicals and chemical disease management), but without the decisive support of a public policy.

The consequence is an increase in uncertainty and a lack of definition: are we dealing with agroforestry systems that are nevertheless introducing dwarf varieties of coffee, better adapted to cultivation under the sun? If so, neither the adaptive advantages offered by SAFS nor the productive benefits of a coffee plantation without shade are being obtained.

We agree with Görg et al. (2017) regarding the urgent need to build an integrative perspective that synergistically incorporates the normative and strategic dimensions of adaptation. Measures that could be incorporated into future coffee management programs to foster an integral adaptation should include explicit attention to present and future climate variability, an insurance mechanism against climate change (Hansen et al., 2007) and financing practices that adjust to the management needs of the coffee growers in the face of biotechnological changes that demand intensification of work and input.

In addition, if the adaptation approach is to be based on biotechnological innovations, it is essential to have the latest developments in biotechnology. New F1 hybrids, of high cup quality, suitable for agroforestry systems and tolerant to a higher thermal humidity gradient, will soon be available in Mexico, although their price is high and their availability will require strong government support. There is, however, a tendency among groups of coffee farmers to return to traditional varieties (Working group of *Sembrando Vida*, a new government program in Talquián and Unión Juárez, field observations during April 2019). Agro-ecological management and selection strategies of coffee seedlings that are resistant to rust in farmers' plots are some of the options being explored by those farmers who have had poorer results with hybrid varieties.

The vulnerability of coffee growers has multiple origins and is expressed in many different ways. Focusing exclusively on a single but fundamental adaptive dimension, that of production, produces a geography of inequality: all of the effort and cost of adaptation falls on the coffee farmer. It also exacerbates tensions between the coffee growers' production needs, the local ecological benefits provided by CAFS, and conditions imposed by an oligopolistic market.

The final lesson offered by this case study is that the adaptation capacity of a particular adaptive practice is not reduced to its technical dimension as if it was inherent within it. Contingency plays a major role in achieving successful adaptation results. Subjective elements, perceptions and the personal situations of those who ultimately carry out the practice of adaptation are influenced by a myriad of factors beyond their reach. Adaptation actions therefore cannot be divorced from the immediate context in which they take place, nor can they be abstracted from those factors at international and national level that might modify the adaptation objectives initially envisaged.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Programme of Support for Research

and Technological Innovation Projects (PAPIIT) and by the head of our research Centre CIMSUR-UNAM. The participants provided their informed consent to participate in the study. We declare that our fieldwork did not involve medical, physical, psychological, or other experiments of such a nature as to interfere with the personal integrity of the participants. Prior to the interview, they were informed of the purpose of the study. The results were returned to them for their knowledge. No personal information was used, and their data was for statistical use only. Permission was also requested from the communal authorities to carry out the study in their territory and to compile the list of those interested in participating voluntarily.

## AUTHOR CONTRIBUTIONS

YM-U: Results, figures and tables, and discussion. CR-d-O: Abstract, intro, theoretical framework, qualitative results, discussion, final remarks, supplementary materials. All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsufs.2021.620422/full#supplementary-material>

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