Yield declines and producer responses to shifting climate and economic conditions in Mexican coffee production

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Abstract

Coffee’s climate sensitivity contributes to extreme production and price fluctuations. However, as coffee is a perennial crop, producers have difficulty responding to short-term market shifts. Combining historical climate, production and price data from all coffee-growing municipalities in Mexico, we examined trends of climate and coffee production and then characterized and quantified coffee producer’s responses to changing conditions of climate and price. We collected and collated production, price, climate and topographic data from Mexican and U.S.

governmental agencies and non-governmental organizations. Using a spatially-explicit approach we found that coffee-specific climate variables contributed to a 60% decline in Mexican coffee production since its peak in the 1989, and that farmers' management responses to soaring temperatures, variable rainfall and price volatility are generally limited to improving yields via management efforts and altering the amount of crop they harvest.

1. Introduction

Coffee is an economically important global commodity, with more than 10 million metric tons grown annually (ICO 2019) across more than tropical 80 countries (Vega 2006). Traditionally grown as an understory crop, coffee provides livelihoods to more than 125 million people (Osorio 2002) most of whom are smallholder farmers dependent on the export of coffee.

Climate change is expected to have widespread impacts on the global coffee supply and coffee producers (Bunn et al. 2015). The coffee plant itself is a long-lived perennial crop, but it is sensitive to temperature, precipitation and microclimate conditions. This climate sensitivity makes coffee especially vulnerable to the effects of climate change and is likely to cause shifts in habitats suitable for growing coffee. Shifts to productive regions will affect all aspects of the coffee supply-chain, but may have strongest impacts on farmers who generally have no alternative to growing coffee and few resources, constraining their adaptive capacity. Given widespread production across many tropical landscapes and dependence of so many farmers and farmworkers on coffee production, farmers' responses to production changes are likely to have massive implications for food and health security, migration and land use change.

Many studies of climate change or weather effects (*e.g.*, El Niño, hurricanes) on coffee employ one of two broad approaches. The first uses forecast models to predict the loss of coffee based on bioclimatic variables at relatively low spatial resolution. These have been helpful to identify those regions most vulnerable to climate change and the scale of threat to coffee production. However, these studies are limited in scope, addressing one or two regional coffee growing areas. These forecast models often lack the precision in spatial resolution that is now more readily available and use models with standardized climate variables rather than climate variables specifically tailored for the study system. For example, WorldClim bioclimatic variables (*e.g.* mean temperature of wettest quarter, mean diurnal range) were developed to be broadly applied to many organismal or ecological systems and are widely used in coffee studies, but may or may not be relevant to coffee production.

Another set of studies has mostly examined producer responses by using interviews and surveys to study farmer responses to dramatic price declines (*e.g.,* Eakin et al. 2006), climate change (*e.g.,* Frank et al. 2011, Harvey et al. 2018) or extreme weather (*e.g.,* Tucker et al. 2010). These studies provided in-depth insight into the complex effects of cultural identities, economics and climate/weather conditions that affect farmers and their responses to stressors. And yet, qualitative studies are often limited in breadth due to time and cost constraints, and may complement a more quantitative approach to examining farmer responses.

Coffee farmers have already observed and experienced issues related to rising temperatures and increasingly variable rainfall (Harvey et al. 2018). And there is now enough available quantitative data to examine initial impacts of climate change and other critical economic variables on coffee production. In this study we couple long-term, spatially referenced coffee production and management data with high resolution climate data to provide a clearer understanding of the various impacts of climate and price on production and how farmers respond. This study provides two unique contributions: (1) organism-specific climate varables and (2) quantified producer responses based on management data.

1.1. *Climate change effects on global production of coffee*

Globally traded coffee consists of two distinct species each with its own characteristics and growing requirements. Robusta coffee (*Coffea canephora*) is produced more commonly in countries of South East Asia (ICO 2019). Robusta coffee can tolerate slightly higher temperatures, but does not produce high quality beans. Higher quality Arabica coffee (*Coffea arabica*) is more commonly grown in Central and South America and East Africa and makes up more than 70% of total commercial production (Ubilava 2012). Although of higher quality, Arabica coffee is more susceptible to temperature variability and is generally grown at higher elevations to avoid extreme high temperatures (Davis et al. 2012).

Several coffee studies have focused on habitat suitability for future coffee production. Indigenous Arabica coffee – the coffee that provides the genetic diversity of Arabica – is facing a nearly 100% loss of bioclimatically suitable habitat in the Ethiopian highlands by 2080 (Davis et al. 2012). Forecasts of commercial coffee in Central America suggest reductions of 30-70% in suitable coffee growing land by 2050 (Laderach et al. 2011). Worldwide estimates suggest a loss of 50% in suitable coffee-growing land by 2050 across all climate emission scenarios (Bunn et al. 2015). Additionally concerning is that most cultivated varieties of coffee comprise a very narrow range of genetic variation (Anthony et al. 2001) relative to indigenous coffee. This reduced diversity of commercial coffee combined with the predominantly self-fertilizing and a long-lived nature of coffee, makes it likely to adapt slowly to climate shifts.

These forecasts are not overly conservative because coffee is particularly sensitive to weather conditions and thus vulnerable to the threats of climate change. This sensitivity is derived from direct impacts on the plant's physiology as well as indirect impacts limiting suitable farming land, and/or increasing pest populations.

Coffee (especially Arabica coffee) has specific water requirements to induce flowers and produce fruits. Floral bud initiation begins during a period of water stress, but flowers open only after initial seasonal rains. As a result, continuous rainfall without at least a short respite of water stress can lead to scattered harvests and low yields (Cannell 1985). At the same time, however, freely available water is required during the period of rapid fruit expansion to ensure the quality of the beans (Lin et al. 2008). And, at any point during the growing season, prolonged droughts and water stress will cause coffee plants to shed their leaves, making them unable to produce flowers or fruits.

Temperature also plays an important role in coffee growth. Arabica coffee is more susceptible than Robusta coffee to extreme temperatures. Specifically, *C. arabica* photosynthesis and growth rates are impeded at daily temperatures below 12˚C and above 24˚C, leaving only a narrow 12˚C window of optimal growth (Nunes et al. 1968). Exposure to temperatures higher than 30˚C for extended periods results in accelerated leaf loss and declines in plant health (Drinnan and Menzel

1995) and at temperatures above 34˚C photosynthetic production stops altogether (Nunes et al. 1968). Likewise, exposure to low temperatures and frost are extremely damaging to coffee. Indeed, cold surges in Brazil during 1994 and 1995 caused 50% declines in production and resulted in dramatic increases in world coffee prices (Marengo et al. 1997, Maizels et al. 1997).

Problems resulting from direct, physiological effects on coffee from climate change will be exacerbated by indirect effects of climate impacts on coffee pests. Several coffee pests are predicted to experience population growth or expansion in response to projected climate scenarios in some coffee growing regions. At least two studies thus far have examined how large-scale changes to temperature and precipitation pattern may impact the distribution and abundance of coffee pests (Ghini et al. 2008). The coffee nematode (*Meloidogyne incognita*) and the coffee leaf miner (*Leucoptera coffeella*) are expected to benefit from to climate change impacts in Brazil. Coffee nematode damage leads to increased root disease characterized by necrosis of coffee tissue and reduced absorption of water and nutrients leading to yield loss and in some cases, plant death (Ghini et al. 2008). The coffee leaf miner causes severe leaf tissue damage that can result in yield loss. Both coffee nematodes and the coffee leaf miner are predicted to increase in infestation and increase the number of generations per year (Ghini et al. 2008). Likewise, climate projections indicate expanded population of the coffee berry borer (*Hypothenemus hampei*). The coffee berry borer is considered to be the most widely distributed and economically damaging coffee pest because the females bore directly into the coffee fruits, rendering them unmarketable (Damon et al. 2000). The climate models of the borer revealed similar results to that of the nematode and leaf miner, but in this case, the authors projected an annual doubling of borer generations as well as upslope migration (Jaramillo et al. 2011). Studies of coffee diseases highlight the importance of temperature and rainfall as factors in predicting incidence and severity of disease (Yáñez-López et al. 2012). More recent studies have emphasized the potential impact of climate change on the coffee leaf rust fungus (*Hemileia vastatrix*) (Avelino et al. 2015, McCook and Vandermeer 2015, Bebber et al. 2016, Liebig et al. 2019).

The sensitivity of coffee to even small changes in climate combined with the indirect effects of pests and disease indicate why coffee is not expected to fare well in under future climatic scenarios where both temperatures are expected to rise and rainfall is expected to decrease and/or become more variable. Yet, future production of coffee is not singularly dependent on climate and weather conditions, because effects from larger global markets, policies and producer behaviors are important consideration in future coffee production.

1.2. *Producer responses to changing conditions*

Farmers are accustomed to variability, but smallholder farmers (≤10ha) are especially vulnerable to production and market volatility as their production is often dependent on rainfed production systems and they have fewer resources and/or lack access to resources (O'Brien and Leichenko 2000; Leichenko and O'Brien 2002). Farmers responses are varied and can include changes in crop management, planting area, crop variety or species and labor costs; but it can also include migration (Eakin et al. 2006, Tucker et al. 2010). Crop management responses encompass changes that focus on increased intensification in one extreme or conservation and agroecological practices on the other. For example, increases in agrochemical and fertilizer use, crop density, shade tree plantings or the maintenance/pruning of crops may be responses to volatile market, climate and production. The type of response from the farmer will depend on their perceptions of risk as well as the type of crop (*e.g.*, perennial, annual), feasibility and financial restrictions farmers face.

Coffee producers are, on average, smallholder farmers and consistently face production losses due to extreme weather or seasonal abnormalities in temperature and precipitation. Surveys and interviews of coffee producers suggest that farmers have observed climate change and its impacts on production but their management responses are mixed and range from adopting no new strategies to expensive long-term changes such as planting alternative crops, increasing/decreasing planted area and tree planting (Harvey et al. 2018). In Mexico, coffee producers report noticing climate change impacts on coffee production – specifically from increased moisture – but also expressed unwillingness to adjust new practices intended to mitigate production impacts from climate (Frank et al. 2011). In contrast, coffee producers in Guatemala, Honduras and Costa Rica said they had adjusted management practices (most commonly planting trees and increasing chemical use) due to experiencing climate impacts (Harvey et al. 2018).

Coffee prices are yet another challenge faced by coffee producers. Volatility of coffee prices is likely to be compounded by climate change as coffee price volatility is often a result of weather-related shocks (Mehta and Chavas 2008). And, prior to the most recent studies, unpredictability in coffee price was identified as the primary concern of small coffee producers over effects of weather, pests and disease, illness and unemployment (Tucker et al. 2010). Producer response to price volatility is difficult to isolate from their response to overall price declines or increases of coffee yields – in other words the difference between long-term variation in price versus short-term price shocks. However, the perennial nature of coffee farming suggests that even though a producer may make changes to their management (*e.g.* increased fertilization, pruning or planting), planting or harvesting area plan after a particular change in price or set of events, decisions are most likely informed by the past volatility of the market. Most research on coffee producer responses to prices studied the impact of low coffee prices of producer decisions in the aftermath of the precipitous decline in global prices from 1999-2003 known as the coffee crisis. These studies found low and variable coffee prices can drive producers to change the total planted area, plant alternative crops, switch to higher value organic production or migrate to the US (Lewis 2005, Eakin et al. 2006, Tucker et al. 2010).

1.3. *Relevance of present study*

Our study seeks to understand the impacts of climate and price on production and producer responses using recent historical data that provide insight into how these impacts have already manifested in coffee production in Mexico. To do so, we first quantify climate effects on coffee production by state over a 27-year period. Then, we characterize producer responses to variations in price and climate (using variables known to be important for coffee development and production) over the course 15-year period by municipality. This lengthy time scale over nearly three decades of data makes this study unique in the area of climate and coffee research and provides substantial data to address our research foci.

Mexico provides an important case study for the changes to coffee production as it is the ninth largest producer of coffee world-wide and the second largest producer in Central America (ICO

2019). Mexico produces high-quality coffee as the second largest producer of organic coffee (Potts et al. 2014) where more than 95% of production is Arabica coffee (Flores 2017) and nearly 90% is shade grown (Moguel and Toledo 1999). Furthermore, coffee-growing regions of Mexico are projected to face increasing droughts and variability in rainfall in addition to rising temperatures (IPCC 2014).

This study is among the first to study and quantify producer responses to prices and climate changes across a large scale of a significant coffee producing country over a relatively long time period of production. Identifying these responses is important to creating policy that aids in addressing specific adaptation needs (Harvey et al. 2018). Ultimately, the results of these realized impacts might better address production and livelihood concerns.

2. Materials and methods

2.1. *Overview*

We performed two separate analyses: (1) an examination of how yields have changed across Mexico, aggregated by state, from 1980-2017 and (2) an evaluation of coffee producer responses to changing climate using biologically relevant coffee climate metrics and economic (*i.e.* price and quality) conditions across Mexico, by municipality, from 2003-2017.

2.2. *Analysis of change in yields and climate, 1980-2017*

To examine the change in yields by state over time, we use annual coffee yields by state for the years 1980-2017 (SIAP 2017) and fit a linear mixed effect model with a random effect of state to examine the change in yields over time by state. We used state aggregated data because data by smaller production units (i.e. municipalities) were not available prior to 2003. The use of state aggregated production data enables us to describe trends in coffee production over a longer, 27-year period. We used linear mixed effects models to evaluate the relationship between yields over time and temperature over time with year as the fixed effect and state as the random effect.

2.3. *Production and climate metrics and extraction to areas of production*

We used annual coffee production, yield and price data by municipality for the years 2003-2017 and joined this dataset with a spatially referenced municipality map of Mexico (INEGI 2012). We used digital elevation models (NASA/METI/AIST/Japan Spacesystems, and U.S./Japan ASTER Science Team 2009) to isolate the regions within each coffee-producing municipality that fall between 400-1600m in elevation. This range is considered the most suitable for coffee production in Mexico under current climate conditions (Laderach et al. 2011). We then separated each 400-1600m elevation range within each municipality into three elevation groups (400-800m, 800-1200 and 1200-1600m) in order to extract more precise climate data for each municipality. Disaggregating in this way is important because climate variability and its impacts on coffee production are likely to exhibit substantial differences across the elevation range, where baseline mean annual temperatures vary from 16º to 26ºC across the 400-1600m change in elevation found in Mexican coffee-growing regions.

We obtained historical temperature and precipitation data at 1×1 km resolution from Daymet gridded monthly averages data (Thornton et al. 2016). Next, we calculated climate metrics especially important to coffee physiology, including the number of months where the average daily maximum temperature was greater than 30ºC, total annual rainfall, and the coefficient of variation in rainfall as a measure of rainfall variability (DaMatta et al. 2007) and extracted these variables for each year and elevation level within each municipality. We specifically chose these temperature variables because they are critical to coffee growth; daily temperatures that exceed 30ºC strongly impede coffee growth (DaMatta et al. 2007). Rainfall variability and total annual rainfall are used in standardized climate metrics (*e.g.,* WorldClim Bioclimatic variables) and are also likely important for coffee given it specific rainfall requirements during flower bud formation and throughout berry expansion. We then calculated a single area-weighted mean across elevation levels within each municipality for each climate variable in each year.

2.4. *Calculation of economic variables*

We chose to use global over local coffee prices to examine price impacts on producer responses. While the local data is available (*e.g.,* farmgate prices used in coffee quality), local data is affected by coffee quality which, in turn is affected by local weather. Therefore, we used the global coffee price from International Coffee Organization's data on monthly historical coffee prices (ICO 2019) as these data are likely to be more independent of Mexican prices. Specifically, we used the 'Colombian milds' price for our global price comparison as it is most similar in coffee taste to that of Mexican coffee's 'other milds' classification, but is likely to be more independent of Mexican prices (Calo 2005). We used the current year's global price as well as one and two year lagged global prices to examine producer responses at various time scales. We did this because management changes in response to price changes may take time to implement and therefore may not be reflected in the same year as the price fluctuation.

To estimate coffee quality, we averaged farmgate prices per metric ton by municipality and year (SIAP 2017), converted it to USD per pound and then adjusted the inflation rate to reflect that of the global price data. We used price per pound of coffee as it is a standard used in international coffee trading markets. We then took the difference between the annual global and local price as an estimate of coffee quality.

2.5. *Producer response analyses*

We examined three different plausible producer responses to external pressures of climate and price, including, (1) change in planted area; (2) proportion of harvested area; and (3) yield, as a proxy for management effort. Change in planted area is the proportional change in area planted in the following year. Producers may choose to plant more or less area in coffee as a direct or indirect result of changes in climate, prices or other factors affecting production. The proportion of harvested area is the total area of harvested coffee divided by the total area in coffee production. Producers may vary the proportion of harvested area due to labor costs or shortages, price fluctuations, quality or climate. Finally, we considered yield (metric tons/ha) as a producer response and proxy for management effort. Producers, for example, may increase management intensity to reduce weeds and pests, prune coffee plants, limit shade trees and/or add amendments to soil – all of which are intended to directly impact yields. We then examined how the climate and price variables affected the three identified producer responses using linear mixed effect models with a random effect of year and state by municipality to account for differences by year and within each location.

3. **Results**

3.1. *Coffee production, 1980-2017*

Overall average annual coffee production (in metric tons) by state has significantly declined since 1980 (Fig. 1, linear mixed model, $p<0.0001$). Since its peak in 1989, total Mexican coffee production has declined by 60.7% and average yields declined by 53.2%. In contrast, total planted area of coffee has remained relatively steady; declining by only 0.2%. Chiapas, Veracruz, Puebla and Oaxaca were by far the largest coffee producing states representing 33.9, 24.7, 15.6 and 14.6% of total production from 1980-2017, respectively while the remaining states each comprised 3.7% or less of total production (Fig. 2a). Trends were similar for planted area (Fig. 2b).

3.2. *Changes in temperature, 1980-2017*

Average annual daily maximum and daily minimum temperatures have increased in coffee-producing municipalities of Mexico since 1980, with a precipitous increase occurring around 2010 (linear mixed model, average minimum temperature: $p<0.0001$; average maximum temperature: $p<0.0001$; Fig. 3).

3.3. *Producer response: change in planted area, 2003-2017*

Neither climate nor economic factors affected a producer's response to increase or decrease planted area over the 15-year period (Fig. 4a, linear mixed model, all factors: $p>0.10$). Indeed, planted area has seen very little change over the past decades relative to other responses (Fig. 5).

3.4. *Producer responses: climate factors, 2003-2017*

Producers did respond to climate factors by altering harvested area and to a greater extent managing yields. The number of months with daily average maximum temperature greater than 30ºC resulted in fewer hectares harvested and lower yields, which may be a biological response to the temperature, but could also be a response of producers to limit harvest if high temperatures result in scattered yields or low quality beans (Fig. 4b, 4c, linear mixed model, harvested area: $p<0.0001$; yield: $p<0.0001$). Similarly, greater variability in rainfall throughout the year (measured by monthly averages) resulted in less area harvested and lower yields (Fig. 4, linear mixed model, harvested area: $p=0.007$; yield: $p=0.01$). Higher total annual rainfall, however, resulted in increased harvested area ($p<0.0001$) and higher yields ($p<0.0001$). There was no effect of the proportion of the coffee habitat at lower elevations within a municipality on area harvested ($p=0.73$) nor yield ($p=0.23$).

3.5. *Producer responses: economic factors, 2003-2017*

Producer's decisions to change harvested area and management of yields varied in response to economic factors. Higher coffee quality resulted in significant increases in harvested area (Fig 4, linear mixed model, $p=0.0002$) and marginally significant increases in yield management ($p=0.05$). Responses to global prices were mixed. For harvested area, the current year's global price had no effect, while the prior year had a significant negative effect ($p<0.0001$) and the global price two years prior had a significant positive effect ($p<0.0001$). For management effort (*i.e.*, yield), the current year's and prior year's global price had no effect (current year: $p=0.44$; prior year: $p=0.18$), while the global price two years prior had a significant negative effect ($p=0.0002$). In other words, global prices in current and one year ago have no effect on management effort/yields but, global prices from two years prior are associated with lower management efforts/yields.

4. Discussion

4.1. *Climate impacts on coffee production*

This study reveals staggering declines in coffee production throughout Mexico during the study period and starting as early as 1989. The decline in production is mirrored by declines in yield but not by total planted area of coffee; suggesting that the documented production declines are related to declines in yield and not as a result of land taken out of coffee production.

Prior research attributes much of the early onset of yield declines to political, economic, and institutional changes (Ponte 2002, Ponte 2004, Eakin et al. 2006). Our research does not contradict these findings, but rather highlights another, likely strong, contributing factor of climate to coffee declines. Indeed, our results indicate that the climate effects on coffee are no longer a future problem, but a current problem as the climate has already negatively affected coffee yields in Mexico. While we expected a negative effect of climate on coffee, the dramatic losses in yield highlight that the sensitivity of coffee to even subtle climatic shifts may be more significant than anticipated. Optimal annual temperatures for *C. arabica* occur between a relatively narrow window of 18-21ºC (DaMatta & Ramalho 2006). But, while average annual temperatures do not appear to have changed much prior to 2000, it is possible that other climatic changes to evening temperatures, humidity, or rainfall variability contributed to these declines which can impact coffee germination, fruit set, fruit load and fruit weight among other productivity characteristics (DaMatta & Ramalho 2006).

Climate suitability mapping has consistently demonstrated the problematic future for coffee given the changing climate. However, many studies rely on standardized climate variables with results that lack strong predictive power across growing regions. The importance of different variables tends to vary considerably by locality and region (Schroth et al. 2009, Laderach et al. 2011, Bunn et al. 2015a, Bunn et al. 2015b, Chemura et al. 2015). For example, 'precipitation of the wettest month' provides the most explanatory power for reduced climate suitability in Nicaragua, but 'mean temperature of driest quarter' has the most explanatory power in Veracruz, Mexico (Laderach et al. 2011). Likewise, in global evaluations of coffee suitability, responses to standardized climate variables varied drastically depending on specified agroecological climatic zones (Bunn et al. 2015b). While these approaches are valuable, especially for large scale assessments at global scales, it would be useful for future studies to consider the use of coffee physiology-specific climate variables as these results are likely to be more consistent across climatic growing localities and regions and thus may provide predictive power in future modelling scenarios. One recent exception, are models that incorporate the effects of rising of CO_2 from climate change on coffee production that employ coffee-specific responses to elevated CO_2. Using temperature and coffee-specific responses to CO_2, DaMatta et al. (2019) find that declines in climate suitability for some regions may be lower than previously estimated.

4.2. *Producer response: change in planted area*

We found strong overall responses of producers in the form of the proportion of harvested area and management investment, but no response in planted area. Only a small fraction of all municipalities recorded any change in planted area over the entire study period (Fig. 5). The low response reveals that changing the amount of land in coffee may not be an easy, economically viable or even feasible response to changing climatic and economic conditions. Several things may explain why changing total planted area appears uncommon. First, from a production perspective coffee are long-lived plants (20-50 years) that are expensive to buy and plant and require 2-5 years after planting before bearing fruit – all of which make it more difficult to increase planted area in response short term changing conditions like price and weather. Second, in much of Mexico, coffee is often grown along steep montane slopes and in otherwise difficult growing conditions, making producing alternative commodity or local crops less appealing. Third, multiple government policies play a role in productive landscapes and land tenure of Mexico. Indeed, until the early 1990's the Federal Government incentivized and encouraged the intensification of farmlands to focus exclusively on coffee production. And, land redistribution efforts from the Mexican government in 1990s also limited the land area held by one family or individuals impeding the ability to acquire additional land. Finally, in several coffee producing areas there may not be additional viable land to cultivate.

4.3 *Producer responses to climate variables*

In harvested area and management effort, producers responded consistently to climate variables. We found that producer responses followed the expected physiological response of the coffee plants. That is, producers harvested more coffee area and increased yields/intensified management effort for higher yields in years with higher total rainfall, but harvested less and reduced management effort and lower yields in years with higher rainfall variability and with more days with high temperatures above 30ºC. Coffee requires an abundance of rainfall, usually at least 1500mm/year, yet the variability in distribution of that rainfall can also affect flower and fruit production. More than any other variable measured, we found that high maximum temperatures had the strongest negative effect on harvested area and yield. High maximum temperatures, especially those above 30ºC, reduce coffee growth, quality and yields (DaMatta & Ramalho 2006).

4.4. *Producer responses to economic conditions*

4.4.1. *Responses to coffee quality*

Producer responses (*i.e.* planted area, harvested area ratio, yield/management effort) to economic conditions of coffee production are less consistent than their responses to climate impacts – with the exception of coffee quality. In years with higher coffee quality, producers harvest more of their crop area and have higher yields. This result suggests that producers are aware of the value of their crop relative to the global market and are able to capitalize on the added value by increasing yields and harvesting more of their crop.

4.4.2. *Global prices and harvested area*

Responses to global coffee prices are not as straightforward as they are to coffee quality and climate. We find that producers do not change the proportion of area harvested during years with higher prices but in the year following a high price year, producers harvest less of the planted coffee area. This discrepancy in response may be because the additional cost of harvesting more area does not translate into increased profits for the producer. Global prices are not always reflected in local markets (as is indicated by our ‘coffee quality’ metric) and do not necessarily translate into higher prices for producers. Mexican producers may also be wary of the volatile coffee market that can leave them vulnerable to exploitative local intermediaries even during high price years (Henderson 2019). Indeed, when prices decline below the cost of production, many producers in Mexico, for example will opt to take wage labor positions rather than harvest their crop (Henderson 2019).

Yet another explanation is that the amount of harvest may be more dependent on the productivity of the coffee itself and may reflect the differences in productivity that arise from biennial bearing. Biennial bearing (*aka*. alternate bearing) is common in many fruiting trees and occurs when trees tend to produce more than average in one year and less than average in the following year. In coffee fruit production this oscillation is not well understood, but it has been attributed to a tradeoff between branch and fruit development (Bote & Jan 2016). In high production years more energy is put into developing fruits at the cost of developing new branches and in low production years more energy is put into branch growth that will support more fruit production in the subsequent year (Bernardes et al. 2012). Some evidence suggests that this cycle can be manipulated to improve quality or increase yields to take advantage of higher prices in a particular year (Bote & Jan 2016). This fruit load management could allow producers to increase fruit loads in one year but may then result reduced fruit loads in the following year.

4.4.3. *Global price, management and yields*

Our findings indicate that management manipulations for contemporaneous and second year yield improvements, if done, are not effective response to global price. In part, this is because the metric of yield that we use as a partial proxy for management effort, is also subject to physiological responses to climate and other environmental stressors. And, while producers may response quickly in an effort to increase yields, the effect of increased yields may occur over several successive years. That is, management efforts may be implemented immediately and in response to increased prices (*e.g.,* pruning shade trees, planting new coffee plants) but the desired effect of increased yields may not be realized for 2-15 years after the management change. By contrast, the producer response to harvest more or less of their planted coffee area is a response that producers can implement immediately and will have an effect in the same year. This may be why the variation in responses is so much lower in harvested area relative to yield changes.

Yields appear to be singularly negatively affected by higher global prices from two years ago, or lower prices now, following high prices. This suggests that increased management effort in response to higher prices in the current and previous year may result in lower years two years later. Likely this is an effect of the delay in management improvements to yields coupled with the physiological biennial bearing of coffee.

4.4. *Data limitations*

While our consistent results provide a level of robustness to some findings, there are several limitations to the dataset that restrict our ability to identify potential mechanisms behind the relationships. First, because data are aggregated by municipality, we were not able to include average farm size as a factor in our analysis, despite the fact that previous studies find that decision making may be influenced by farm size (Haggar et al. 2013). This data is important because the behavior and response of producers may change depending on how much land they have in production or how much funding they have to pay laborers to harvest. We also lacked data on production type (*e.g.* organic vs. conventional) or shade management. Shade trees in coffee production can maintain cooler surface air temperatures, humidity, soil water retention and may improve natural pest control services or pollination (Jha et al. 2014). The effect of shade trees on coffee production at this scale may provide some insight into the future of coffee production in mitigated long term climate effects on production. Finally, this data set does not distinguish between Arabica (*C. arabica*) and Robusta (*C. canephora*) coffee plants. Robusta coffee produces beans that are much lower in quality than that of Arabica, however the plant is less sensitive to climate, pests and diseases and produces higher yields. About 95% of coffee produced in Mexico is Arabica (Gay et al. 2006), yet Robusta is expected to grow in popularity and may provide another way for producers to adapt to the changing climate conditions. Should Robusta begin to replace Arabica throughout Central America this may result in increased yields, but lower prices to farmers as it produces lower quality beans.

5. Conclusions

Climate change has already impacted coffee production and producer decisions in Mexico, currently the tenth largest producer of coffee in the world. In high elevation coffee-growing regions maximum temperatures are now about 30ºC – which is document here and in other studies as having a strong negative impact on the coffee plant and coffee production. At the same time, coffee prices continue to be very volatile, exacerbating the ability of producers to respond. Generally speaking, higher consumer coffee prices do not translate into higher prices for producers. However, should climate severely reduce global coffee supply, prices to coffee producers may increase. This study indicates that coffee producers cannot generally capitalize on high market prices, but still have some capacity to adapt to changing conditions that is limited to harvesting capacity and management efforts to improve yields. Yet, under more extreme weather conditions producers may not be able to increase yields or may not gain additional benefit from harvesting more land, thus limiting their capacity to adapt.

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Author Contributions

KKE conceived of the study and KKE and SMP collected the data. KKE, PQ, KZ and AMB helped with data processing. KKE conducted the data analyses and visualizations. KKE wrote the manuscript. PQ, KZ, SMP and AMB provided feedback and edits on the manuscript.

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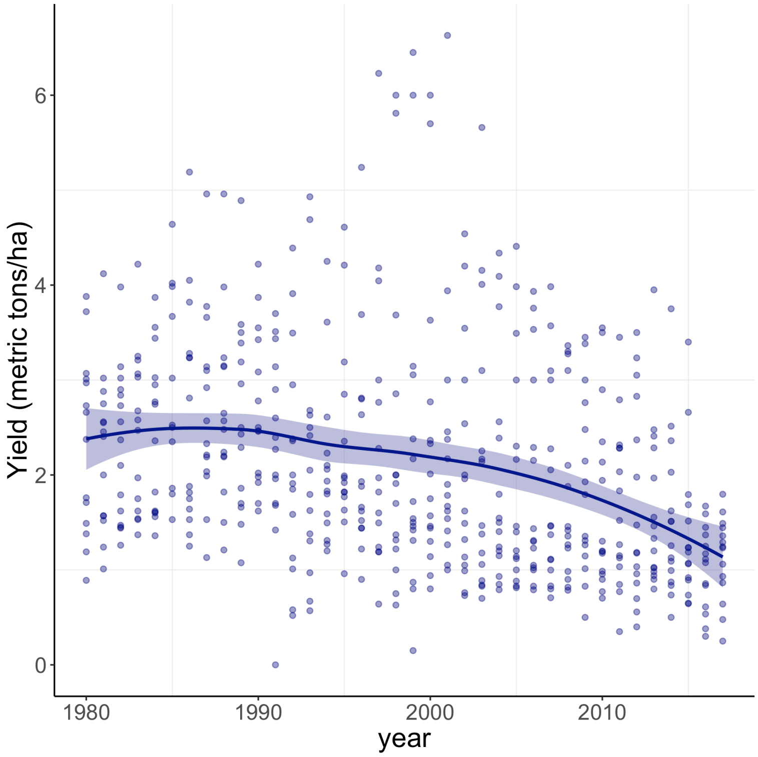
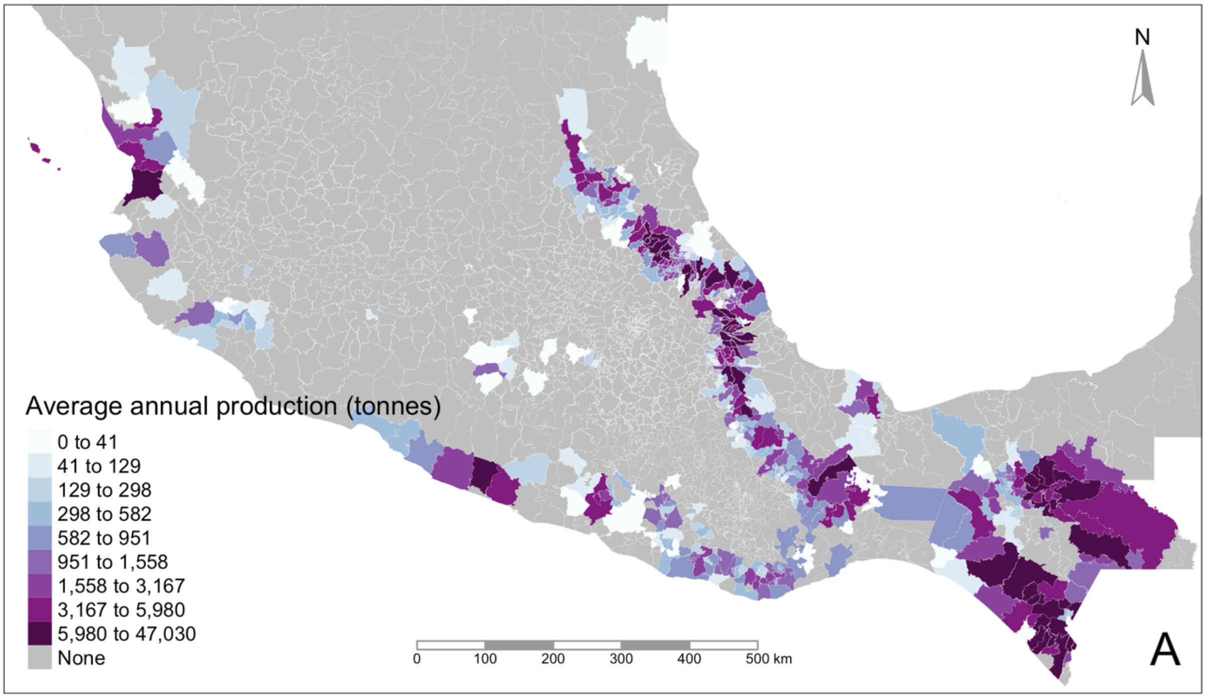


Figure 1. Average annual coffee yield by state, 1980-2017.


N
Average annual production (tonnes)
0 to 41
41 to 129
129 to 298
298 to 582
582 to 951
951 to 1,558
1,558 to 3,167
3,167 to 5,980
5,980 to 47,030
None
0
100
200
300
400
500 km
A

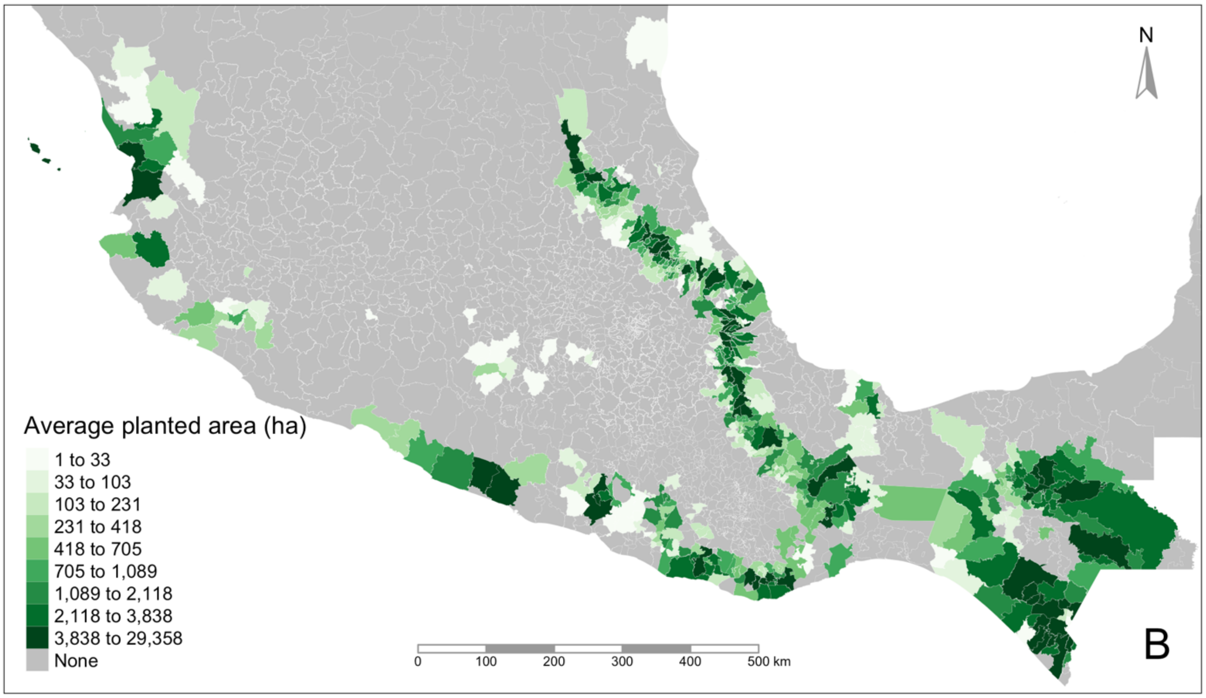

N
Average planted area (ha)
1 to 33
33 to 103
103 to 231
231 to 418
418 to 705
705 to 1,089
1,089 to 2,118
2,118 to 3,838
3,838 to 29,358
None
0
100
200
300
400
500 km
B

Figure 2. Map of (A) average annual production by municipality averaged from 2003-2017 and (B) total average area planted (ha) in coffee.

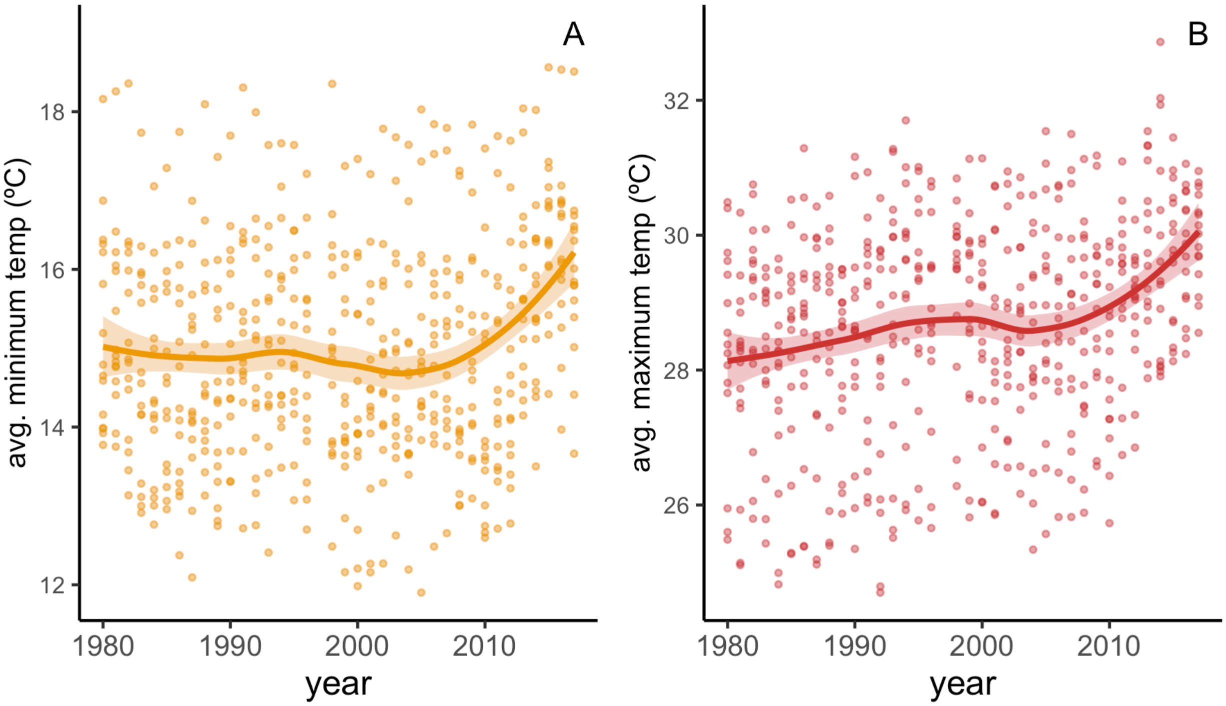


Figure 3. Average monthly (A) maximum and (B) minimum temperature for elevations between 400-1600m in elevation within coffee growing municipalities (weighted proportionally by elevation area within each municipality), 1980-2017. Data fit with locally-weighted scatterplot smoothing (LOESS).

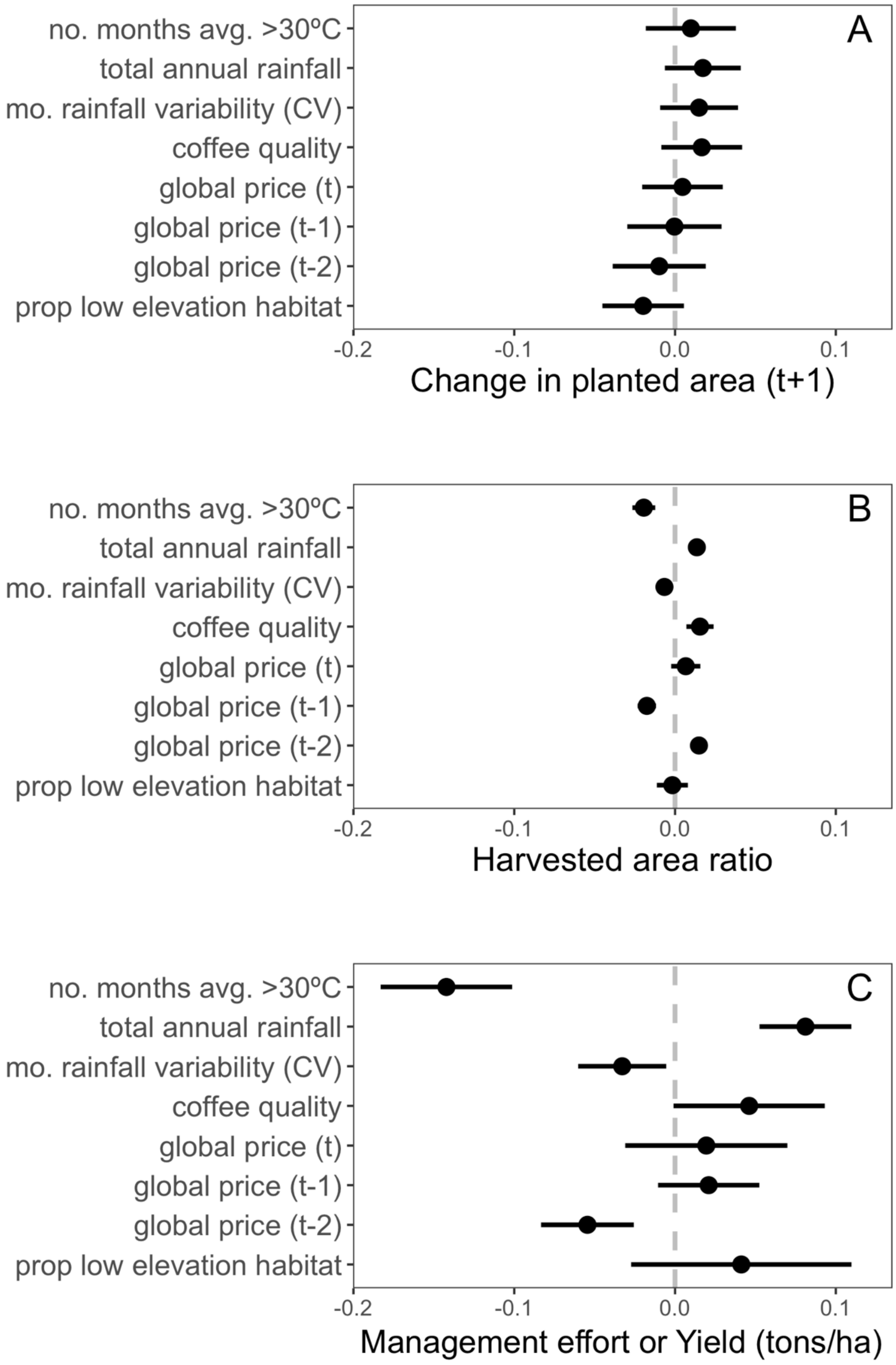

A
no. months avg. >30ºC
total annual rainfall
mo. rainfall variability (CV)
coffee quality
global price (t)
global price (t-1)
global price (t-2)
prop low elevation habitat
-0.2
-0.1
0.0
0.1
Change in planted area (t+1)
B
no. months avg. >30ºC
total annual rainfall
mo. rainfall variability (CV)
coffee quality
global price (t)
global price (t-1)
global price (t-2)
prop low elevation habitat
-0.2
-0.1
0.0
0.1
Harvested area ratio
C
no. months avg. >30ºC
total annual rainfall
mo. rainfall variability (CV)
coffee quality
global price (t)
global price (t-1)
global price (t-2)
prop low elevation habitat
-0.2
-0.1
0.0
0.1
Management effort or Yield (tons/ha)

Figure 4. Standardized regression coefficients of coffee producer responses of (A) change in planted area (B) proportion of harvested area and (C) yield to changes in climate and price.

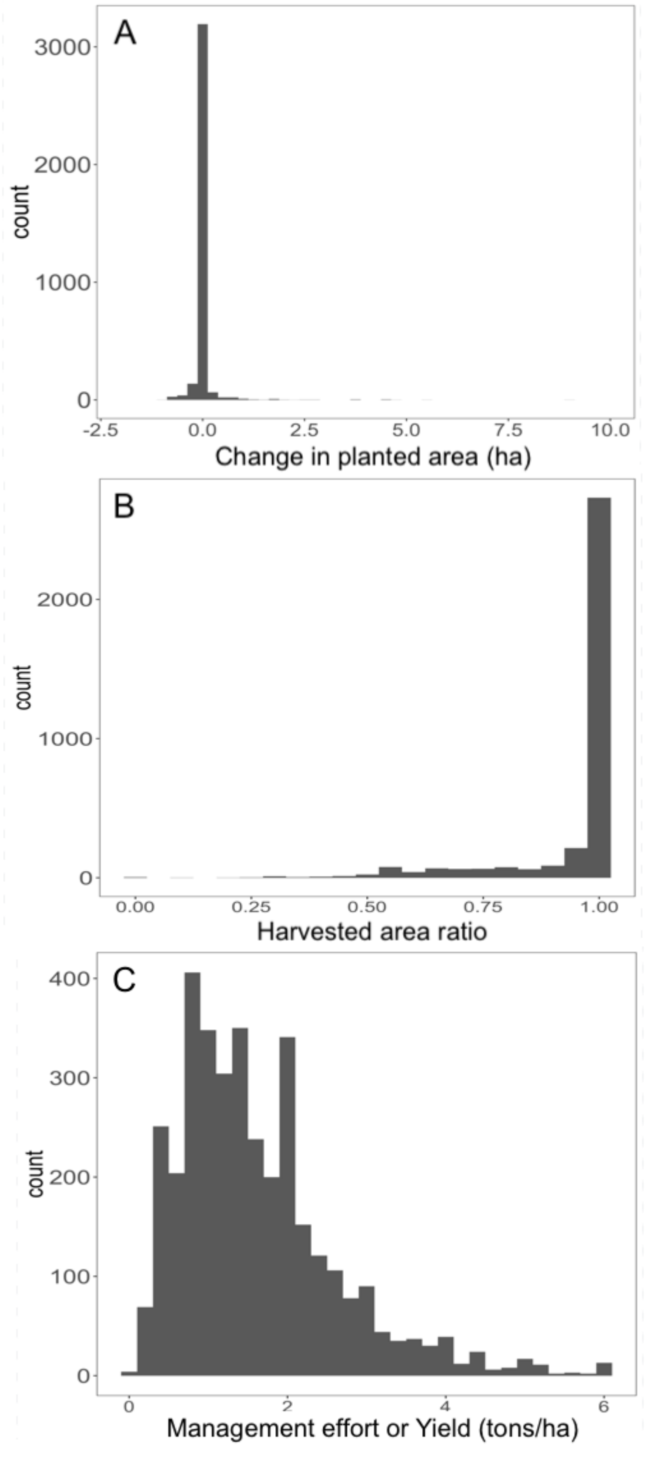


Figure 5. Frequency distributions of producer responses for (A) change in planted area, (B) harvested area ratio and (C) management effort.