

Research



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Small-scale farmer responses to the double exposure of climate change and market integration

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Anthropologists have long studied how small-scale societies manage climate variation. Here, we investigate how Yucatec Maya subsistence farmers respond to climate stress, and the ways in which market integration may enhance or disturb response strategies. Using information on harvest returns, climate perceptions, household economics and helping networks, modelling results show that as farmers rely more on market inputs (e.g. seed, tractors, fertilizer) for a successful yield, the reasons given for a bad harvest shift from climate variables to access to quality inputs. We also find that social and economic diversification is key to mediating a household's experience of climate and market shocks. The Maya are astute stewards of climate knowledge, and have effective social and economic means to mitigate potential fluctuations in food availability. In the transition from a subsistence to a market integrated economy, these traditional strategies become strained. Reliance on market inputs forges a more rigid food production system that conflicts with the diversity and flexibility on which traditional strategies depend to manage climate variation. Moving forward, the best policies would be those that facilitate maintaining an equal footing in both a subsistence maize economy, while incorporating new market opportunities.

This article is part of the theme issue 'Climate change adaptation needs a science of culture'.

1. Introduction

Subsistence agriculturalists are well adapted to interannual climate variation. Farmers manage seasonal and annual fluctuations in food production by relying on fallback foods, diversifying production [1] and having well-developed alliance and exchange relationships [2,3]. However, if climatic perturbations become too great or directional, as occurs during climate change (e.g. persistent drying trends or more pronounced storm cycles), consequences can be profound for small-scale farmers whose livelihoods are directly tied to food production. Indeed, small-scale subsistence societies are some of the most susceptible to the effects of climate change [4].

In small-scale societies, climate stress on food production often is compounded with challenges associated with market integration, a dual effect referred to as the *double exposure* [5]. Climate fluctuations can make agricultural production less dependable [6], while at the same time a growing body of research identifies smallholder farmers as particularly sensitive to the negative impacts of market integration [7–9].

For small-scale societies, market integration is a process involving increased social and commercial interaction with non-local entities and often a blending of traditional subsistence production with the labour market (e.g. wage labour, cash economy and surplus production) [10]. Because these mixed economies have a foot in two different livelihoods with different sets of risks and means to offset downturns, households must balance investments in traditional subsistence practises and social behaviours with new, unfamiliar ways of making a living [11,12]. Exposure to novel but often uncertain opportunities may interact with

climate stress. For example, volatile market prices or unreliable access to agricultural inputs (e.g. seed, fertilizer) may compromise the ability to adapt subsistence practises to climate variation [13,14]. Thus, poor livelihood outcomes may result from either climate change or market forces. Distinguishing between these forces, and their interactions, is significant to avoid diluting or obfuscating climate stress problems might instead arise from market integration.

(a) Strategies to offset shortfalls in food production

To buffer against climate stress and potential shortfalls in food production, both the archaeological and ethnographic records show that small-scale societies may either diversify their resources base, or intensify particular resources [15–18]. In the past, new resources (e.g. fish, seeds) or strategies (e.g. processing food) were added to the subsistence base in some instances, and in others they replaced previous foods and technologies [19], as in the transition from hunting and gathering to committed agriculture. In the contemporary context of market integration in small-scale societies, cash becomes the currency of exchange and is often needed or desired to buy market foods, medicine, manufactured tools, and vehicles or to pay for school fees or hospital visits. Cash can be generated by diversifying a household's economic activities, and/or intensifying resource production [20]. Examples are growing surplus crops or raising domesticated animals for the market, or incorporating wage labour, craft production or tourism into traditional economic portfolios.

Beside intensification or diversification, social support networks are another well-documented means to buffer against climate fluctuations and shortfalls in food supply [21–23]. While traditional sharing and support networks vary according to subsistence and ecological demands, these networks are often characterized as homogeneous, reciprocal and primarily based on kin [24,25]. The strength of such networks is argued to come from network closure, which helps buffer individuals from resource loss and promote equality among individuals [26–28]. However, the process of market integration may disrupt these safety mechanisms, exacerbate vulnerability to climate change and pose new threats to household well-being [29–31]. At the same time, market integration may introduce new beneficial social relationships, such as access to formal assistance institutions [30,32]. This double-edge effect means that people in mixed economies often maintain traditional sharing and cooperative bonds [33,34], while pursuing new institutional and social relationships [35]. Households may benefit from increasing exposure to those outside their community to use contacts with employment or aid opportunities [36,37]. Households that diversify their income base may be more inclined towards outward-looking networks, while local and kin-based sharing networks may better serve those that intensify agricultural production as a means to participate in the cash economy.

While Maya farmers have well-developed strategies to cope with climate variation, recent market integration creates new opportunities and challenges to these traditional strategies and to their food production system. To investigate the impact that the double exposure has on small-scale systems, we consider its influence on the livelihoods of Yucatec Maya maize farmers. Our analytic goals are to parse how Maya farmers view the effects that climate and market factors have on harvest outcomes, and to uncover the social and economic

characteristics that place some families at greater risk of experiencing a bad harvest year. To do so we use multi-prong climate, economic, demographic and social network data collected over several years. These include structured and semi-structured interviews with Maya farmers focused on gathering information about their perceptions of climate change, their assessments of harvest outcomes, the climate and market causes they give for those outcomes, and quantitative data on social networks and household economic strategies. To contextualize farmers' responses, we situate our findings in the background of longitudinal, fine-grained climate and market data from the Yucatan Peninsula.

Mixed economy studies have identified the cascading effects that market involvement has on subsistence and Indigenous communities [11,12,35,38,39]. This study emphasizes the value of what Indigenous people, who live close to the mode of production, have to say is important about the climate and market impacts on their livelihoods. Parsing these forces is a valuable policy and development tool to construct programmes and interventions appropriate to the distinct pressures that climate versus market forces may generate.

2. Ethnographic and climate background

(a) Ecology

The Maya study population lives in the remote *Puuc* region of the central Yucatan Peninsula, Mexico. Despite Yucatan's tropical climate and abundant rainfall, surface water for domestic use is limited. The Yucatan's flat topography and porous limestone substrate confines surface water to isolated dissolution basins that form in the caprock. These are known by numerous names depending on size and depth, e.g. *cenotes*, *sartenejas*, *chaltuns*. The rural Yucatec Maya today, as throughout the colonial and precolonial periods, manage living on a landscape without running surface water by residing in small dispersed communities. The Puuc receives approximately 1100 mm of rainfall annually, however, the small size and sparseness of surface water in this part of the Yucatan constrains the distribution of human populations even more than elsewhere in the Yucatan.

(b) Maya farmers

The Indigenous Maya who inhabit this rural region, hereafter referred to as the Yucatec Maya, live in small farming villages and hamlets, and in a few larger market and administrative towns (electronic supplementary material, figure S1). Multi-generational economic, demographic and social network data have been collected in the study community since the early 1990s [40–43]. Although many economic, social and demographic changes have occurred in recent years since a paved road was built into the village in 2003 [12,44], maize farming remains the predominate livelihood (small-scale farming is the primary occupation of 96% of households). Most families grow their own food and maize constitutes about 80% of the diet.

What has changed in recent years is an increased diversity in many aspects of their economic lives. Prior to the paved road, all families made their living as subsistence farmers (less than 3 ha under cultivation), with nominal engagement in cash cropping, the labour market or the regional economy [45]. The need for cash was minimal, and wealth was measurable by household

size and the labour force to produce food [12,35]. The road and subsequent access to markets, vehicles and mechanized farming opened up new ways of making a living, including travelling to wage labour jobs and producing crops for market. Cash is increasingly vital to fund agricultural intensification—to pay for tractor use, seed, fertilizer and vehicles to transport crops to market. Not all families, however, have the resources to intensify equally. Observable consequences include a significant increase in variance among villagers in wealth, fertility, education [12] and livelihood diversity [11]. For instance, while the average amount of land a household has under cultivation has increased, the variance has more than doubled since the early 1990s (1992 mean = 2.6 ± 1.1 ha, range 1.0–5.5 ha; 2021 mean = 6.6 ± 5.6 , range 0–40 ha). At the community level, the population is transitioning from economic homogeneity to increasing heterogeneity.

(c) The agricultural cycle

In the otherwise flat landscape of the Yucatan Peninsula, the Puuc ridge (maximum elevation 250 m) segregates the coastal plain to the north from the Petén lowlands to the south. The low canopy, neotropical forested hills are interspersed with savannahs, affording a variety of micro ecozones [46]. Prior to the road, the hill slopes, where water retention and nutrient-rich soils are best, were the preferred landform to farm. With the introduction of tractors and fertilizers, maize cultivation has expanded into the broad, flat savannahs, which have poorer soils, but are more accessible. While some larger towns in the region now irrigate, agriculture in the study community is exclusively dryland farming.

The agricultural cycle begins in late spring when the underbrush is cut and burned to remove the secondary growth, rejuvenate the soil, and control insects and other vermin. Burning is timed before the onset of the rainy season to avoid the nutrient-rich ash from washing away. Fields are planted from mid-June to late August when the ground is moist but not saturated, so that the seed will germinate but not rot. If farmers plant too early, the young plants may not thrive for lack of water, and if too late, the plants may not be sufficiently mature to withstand heavy late growing season rains. Maize takes two to three months to mature, and is harvested from September to November.

In 2019, Maya farmers for the first time began talking about climate change and its effect on the agricultural cycle. In directed interviews with 101 farmers, 88% ($n=89$) of participants say that bad harvest years are occurring more often, and 77% ($n=77$) say that they think climate change has affected their frequency (table 1).

(d) Climate variation during the agricultural cycle

Daily rainfall averaged across the 60 years that meteorological data are available for the Yucatan Peninsula (see Climate data in the Methods section) depicts a six-month *dry season* (the non-growing season) from approximately November to April, when rainfall is relatively low, averaging less than 5 mm per day (see baseline on figure 3). The six-month *wet season* (the growing season) from approximately May through to October is described by a bimodal rainfall pattern, where a midsummer dry spell (*canícula*) is bracketed by periods of rainfall maxima. The late growing season rainfall maxima (averaging greater than 8 mm per day) coincides with the Caribbean tropical storm and hurricane cycle. Importantly, the precipitation record reflects how the Maya farmers

Table 1. Responses ($n=101$ households) to the directed questions about climate and market effects on harvest outcomes.

	yes (%)	no (%)	no opinion (%)
do bad harvest years occur more frequently?	88	3	9
does climate change affect the frequency of bad harvest years?	77	7	16
are market inputs (price or quality) responsible for a bad harvest year?	50	41	10

themselves describe the annual rainfall cycle, when they schedule agricultural activities, and when vulnerabilities to crop loss occur during that cycle.

Long-term trends show that precipitation has increased by approximately 5 mm per year since 1953 [47], and that rainfall has disproportionately increased during the rainy season (May–October), and specifically during the late growing season. Of the rise in rainfall over the last 60 years, 73% has occurred during the rainy season and 82% of that increase during the months of August to November, which overlaps with the tropical cyclone season when heavy rainfall can flood fields, and together with considerable winds can damage crops [47].

Putting the agricultural cycle and climate data together, local Maya farmers' climate concerns overwhelmingly centre on the timing and intensity of growing season rains. Crops are most vulnerable to either too little or too much rain during the midsummer dry spell (*canícula*) and during the cyclone season. Of these, the latter has the greatest potential negative impact on harvest yields. Excessive rain late during the late growing season is particularly destructive because, while farmers have an opportunity to replant if the *canícula* is prolonged, they do not if mature crops are destroyed at the end of the growing season.

(e) Traditional strategies to mitigate climate variation

Prior to the road and engagement in the market economy, Maya farmers expected poor yields to occur several times a decade, and planned for them [40,45]. In some years, livelihoods might be disrupted by an extreme climate event, such as a tropical cyclone. In 2002 Hurricane Isadore, a late growing season storm depleted approximately 70% of crops. Nine other named hurricanes made landfall in the state of Campeche from 1988 to 2023. The Maya reduce the risk of crop failure and food shortages by planting in multiple locations to offset the geographical vagaries of rainfall (both too much and too little), by staggering when they plant across the growing season and storing enough maize to get through a bad harvest year.

(f) Good and bad harvest years

For smallholder agriculturalists, whether a household has a good or bad harvest year influences many downstream measures of wellbeing. Previous work showed that bad

harvest years were associated with a drier than normal mid-summer dry spell, and heavy rains brought on by tropical cyclones [47]. While a relationship between climate and food production was evident, it also raised new unanswered questions about the influence that the introduction of a road and changes in farming practices had on food production.

(g) New market forces

While the community historically managed climate variation, before the road was built market forces had little influence on harvest outcomes. Shifting from subsistence farming (growing enough food for household consumption) to production for the market depends on purchasing agricultural inputs (e.g. new hybrid seed varieties, fertilizers, pesticides, vehicles and tractor rentals). For people who do not have a cash base, inputs are purchased on credit and debts repaid at the end of the growing season when crops are sold. Commodity values, and particularly market shocks, impact whether farmers can repay their loans or are pushed further into debt. As examples of local market shocks since 2003, the price of maize halved from June 2013 to June 2014, falling from MX\$679 metric ton⁻¹ to MX\$300 metric ton⁻¹ (informant reported; figure 4). In 2017, the bottom fell out of the honey sales owing to European Union (EU) restrictions on imported honey (much of the honey that Mexico commercially produces is exported to the EU), and in 2018 the market for x'ka (squash seed) collapsed. For subsistence farmers, for whom high yields are always better, the market-based concepts of supply and demand and the non-intuitive precept that high yields push down value, are foreign.

With these new market considerations, here we ask how farmers explain harvest outcomes, whether their explanations are associated with climate or market variables, and whether a household's social and economic resources mitigate these experienced harvest outcomes. To address this: (i) we first establish how Maya farmers assess annual harvest returns in each of the past three years (2019–2021), with an interest in whether there is consensus or variation among households; (ii) we then examine the reasons that Maya farmers give for the causes of harvest outcomes, and the weight given to climate and market factors; (iii) these explanations are contextualized with background local precipitation and market data; and (iv) we then model whether a household's composition, social or economic resources predict whether farmers experience a harvest year as good or bad.

3. Methods

(a) Data collection

To address our study questions, we take an in-depth view of a Maya community whose transition from a subsistence to a market-integrated economy has been extensively studied since 1992 [11,12,35,40,45]. Household interviews were conducted in two rounds. The first round, from 2017 to 2018, collected detailed information about household social support networks, and economic diversity. During the second round in 2022, interviews focused on household demographic composition, harvest assessments, the climate and market causes of harvest outcomes, economic resources and agricultural production over the previous year (i.e. in 2021).

The Maya study population is comprised 533 individuals, 73% are over the age of 15. The 160 biological families (parents and

children) are organized into 104 households, or sharing groups (defined as clusters of families that share economic resources, based on observational and interview data), of which 101 (97%) are included in this study (three households did not participate). During both rounds, interviews were conducted with the male and female household heads present. These data provide a comprehensive picture of household livelihoods, and their experiences with the dual impact of climate and market forces.

(i) Yearly assessments and causes of good and bad harvest outcomes

Household interviews consisted of structured questions targeted whether each of the last three growing seasons (2019–2021) was a good, normal or bad harvest year. Follow up open-ended questions solicited explanations for their perceived causes of good and bad years. Male and female household heads readily answer these questions and willingly offer insights about agricultural production. We note that although years previous to 2019 were inquired about, participants were forthcoming in saying that while they could retrospectively distinguish details about the previous three years, they were reluctant to commit specific descriptions about years prior to that. Of the 101 participating households in the 2022 survey, 101 households (100%) gave harvest assessments for the year 2021, 99 (98%) for 2020, and 94 (93%) for 2019 (electronic supplementary material, table S2).

(ii) Household social and economic resources

To model whether some households are more or less likely to experience a bad harvest year, information was collected on social and economic resources and household composition. A household's social resources were elicited by asking male and female household heads to nominate individuals with whom they cooperate in agricultural work, that is individuals who have helped at harvest time or with any other field labour. From this agricultural helping network, we measure *degree centrality*, or the total number of helping partners a household has listed. Household heads were also asked about helping behaviours across a wide range of domains, including borrowing and lending money and items, labour support, domestic help and ties to individuals in government or non-governmental organizations. From these, we calculate *external ties*, or the total number of individuals in a household's social network who live outside the village. Additionally, *household size* is used as a measure of within household support.

A household's economic resources were parameterized several ways. *Tons per hectare* (TPH) is a household's reported tons of maize produced divided by the total number of hectares they have under cultivation. *Government subsidies per capita* sums the total remuneration a household receives from government programmes, divided by the total number of adults in the household. Many of these programmes are aimed at mitigating resource shortfalls faced by rural farmers. (Locally available subsidy programmes in 2021 include *Sembrando Vida* (tree planting programme), *Apoyo para Campo* and *Bienestada Social* (agricultural programmes, formerly Procampo), *Benito Juárez* and *Jovenes Escribiendo el Futuro* (subsidies for students), *Conafor* (conservation programme), *Terceraedad* (old age stipend) and *Descapacidad* (subsidy for disabled children).)

Economic diversity is an index of the number of economic activities performed by adults (greater than age 15) in a household. Possible activities include wage labour, agricultural work, piece work, domestic work, attending high school, or other preparatory school, and professional work. These activities are summed across the household (1–6) in a diversity index. *Agricultural diversity* totals the number of crops beside maize that a household cultivates (0–4). Alternative crops include peanuts, beans and squash varieties grown for their seeds. In addition, *honey production* indicates

whether a household raises bees. Honey for commercial sale has increased over the last 20 years since the road permitted access to markets. In 2021, 39 households (43%) produced honey for the market (mean = 171.9 kg, range 0–1800 kg).

Two variables are added to control for household demographic composition. *Age of the household* is the age of the adult male household head. If the household has no adult male head ($n = 4$), the female head's age is used. *Established household* is a binary term indicating whether a household was established prior to 2017, or has been formed since then. New households consist of adult sons who married and built their own economic unit distinct from their parents between 2017 and 2022. Younger and newly formed households are typically smaller, have fewer adults pooling economic resources, and smaller land holdings [11].

(iii) Regional climate and market data

To ground participant responses, we situate them in the local context using climate and regional market data. High-resolution climate data are available from the Mexican National Meteorological Service, which has maintained a network of 200 weather stations across the Yucatan Peninsula for some 60 years (accessible through the government's website <https://smn.conagua.gob.mx/es/climatologia/informacion-climatologica/informacion-estadistica-climatologica>). We aggregate daily precipitation from the four weather stations that are in closest proximity to the study community (within 40 km) and have continuous data through to December 2021. (Station recordings began in 1953 for the Bolenchen weather station, in 1958 for Muna and in 1969 for the Santa Elena and Xul weather stations.) This synthetic local weather station was constructed by averaging daily measurements across the four stations to generate a daily rainfall mean. To contextualize the market environment in which rural Maya farmers are operating, we use government published reports for non-irrigated maize yields and the market price of maize for the rural municipality (an approximate 7500 km² area) in which the study community is located (database available since 2003 for rainfed maize at http://infosiap.siap.gob.mx/gobmx/datos/Abiertos_a.php).

(b) Analytic methods

(i) Yearly assessments and causes of good and bad harvest outcomes

The distribution of explanations given for each of the three harvest years (2019–2021) was based on open-ended responses describing each year, and coded using a multi-step iterative coding process. In the first step, the verbatim responses are transcribed, and a short phrase or word extracted to summarize the presence of a topic, theme or idea. The initial set of codes included a mix of deductive codes that we expected from previous research to be explanations for good and bad harvests, such as tropical storms, hurricanes, the duration of the *canícula*, amount of rain or the market price of maize, and inductive reasons that emerged from the interviews, such as hot night rains, the quality of seed and fertilizer.

Six student research assistants independently coded the translated verbatim responses ($n = 335$), and inter-coder reliability was assessed for each response using the Cohen's Kappa statistic [48]. Coding was discussed in laboratory meetings, and the code book refined accordingly. The dataset was then recoded with the updated code book. After three rounds of recoding the verbatim responses, intercoder reliability was sufficiently high (the mean Kappa was greater than established threshold of 0.9 across the code book) to indicate high congruence or reliability among coders. In the final iteration, coding conflicts were resolved by majority rule, meaning four out of the six coders agreed that a code was present or absent.

The final code book includes 49 reasons given for a good or bad harvest, which were grouped into three themes: climate, market

and agricultural explanations (electronic supplementary material, table S1). *Climate* explanations were responses that mentioned any aspect of the weather, typically rain, but also including cloud cover, wind, heatwaves and hurricanes. *Market inputs* refer to aspects of either the cost or quality of agricultural inputs used by farmers, as well as the price of corn. Finally, *Agricultural* explanations describe the crops themselves. Examples include growth performance over a season, flowering, pests, diseases and overall yields.

(ii) Modelling the likelihood of having a bad year

To model the likelihood of a household reporting a bad year (0,1), we use a logistic regression with a log link function. Predictor variables include social and economic resources, and household demographic composition. Our final modelling approach depends on whether we find sufficient yearly variation in harvest assessments. If there is enough variance, a multi-level model with a random effect for 'household' and a fixed effect for 'year' (2019, 2020, 2021) will be used. If assessments do not vary across years and households (i.e. very few households rate a year as bad, or in only one year do households indicate they had a bad year), a simple logistic regression will be used, without the need to account for clustering. Only households that had data for all household composition, economic and social resource predictors were included in the modelling sample ($n = 87$, 86% of the 101 participating households who gave yearly assessments). We conducted a sensitivity analysis imputing data for missing values for the full sample (electronic supplementary material, table S6), to assess the correlations between economic predictors (electronic supplementary material, table S4) and employ a model selection procedure to evaluate and validate the parsimony of the final model (electronic supplementary material, table S5).

4. Results

(a) Yearly assessments of harvest outcomes

Local Maya farmers clearly distinguish 2019 and 2020 as normal-to-good harvest years, and 2021 as having a poor harvest outcome (figure 1; electronic supplementary material, table S2). The majority of households concur in their assessments; 98–99% of households agree that 2019 and 2020 were normal-to-good years, and 78% of households that 2021 was a bad harvest year.

(b) Causes of good and bad harvest years

When household heads were asked to describe the reasons for each yearly assessment, as a first-order observation, most mention both market inputs and climate features in all three years, with a few adding agricultural aspects such as yields, maize growth or pests (figure 2, top panel). Notably, in 2021, which most households ranked as a bad year, the quality and quantity of market inputs were the most prominent reasons given, and reported with greater frequency than during good years.

When explanations are disaggregated (figure 2, bottom panel), the most common market input response in defining a bad harvest was poor-quality fertilizer, with a number of farmers commenting that the fertilizer was mixed with filler and did not dissolve. The widespread adoption of commercial fertilizer is relatively recent, and market inputs have quickly emerged as a key determinant of agricultural assessments.

Of climate explanations, most described the frequency, timing and quality of rain throughout the growing season. A number of farmers point to *x'cang'bul*, the Yucatec Mayan for a visible blight on maize leaves that is the consequence of rain

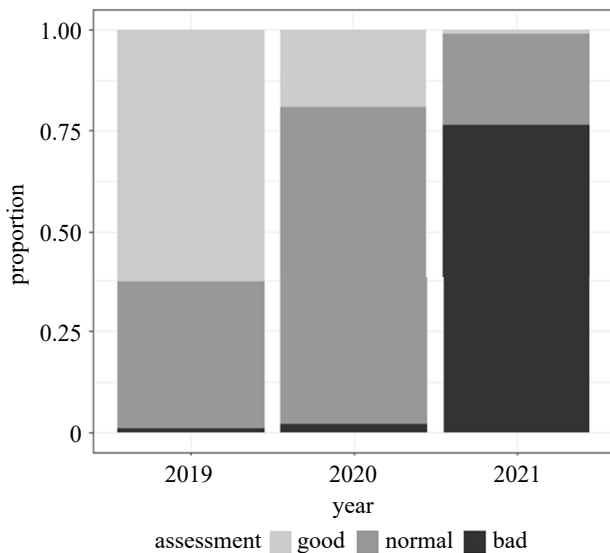


Figure 1. Yearly harvest assessments. Proportion of Yucatec Maya households who rank a harvest year as good, normal and bad.

that falls hot and at night, as a key cause of a bad harvest. Night rain was not mentioned as a factor that negatively affected harvest outcomes in agricultural surveys conducted previously in this community in 1992, 2003, 2010 and 2017.

Both poor-quality fertilizer and night rains are new causes attributed to low harvest returns. In the words of farmers, 'The rain fell at night after heating up all day in the clouds'; 'Night rains aren't normal, and blight the little plants'; 'more than anything, the fertilizer given by the government is useless'; 'It doesn't have nutrients in it'; 'It's like cement, it doesn't dissolve, even after months'.

(c) Contextualizing responses with climate and market data

To contextualize Maya farmers' assessments, we backdrop their responses in the local precipitation record and the government-published market database for the relevant years (2019–2021). When compared to precipitation across the 60 years that Yucatan's weather data are available, monthly rainfall during the growing season falls within a standard deviation in each of the study years (figure 3; an exception is June of 2020 when it rained more than 150 mm per day for a 3-day period). However, differences between normal-to-good and bad harvest years are apparent when compared to the 60-year average baseline. The normal-to-good years of 2019 and 2020 have rainfall that is both sufficient and minimally variable during the growing season. However, compared to the baseline, 2021, which study participants generally characterized as a bad harvest year, had particularly heavy rainfall both at the beginning and end of the growing season, and a more pronounced *canícula*. Of the three study years, July of 2021 was the driest month, and August and September the wettest, followed by an unusually dry October. These weather characteristics are consistent with our previous finding that a pronounced *canícula* and heavy late growing season storms are associated with lower than normal harvests [47].

The municipal market data over the 20 years that they are available show that as local Maya farmers start to participate in the market after the road was built in 2003, prices ascend, with a precipitous market shock between 2012 and 2013

when prices halved and stayed low for a number of years before rising again, with a smaller shock occurring between 2016 and 2017 (figure 4).

(d) Predicting a household's likelihood of having a bad year

Most households (76%) ranked 2021 as a bad year, but not all; 24% of households classified as normal or good. Are households who ranked 2021 as a bad year distinguished in some way? Using household composition, social and economic resources as predictors (table 2), model results show that some household characteristics are associated with a higher chance of experiencing a bad year (table 3).

Households that had higher odds of ranking a year as bad had more individuals in their agricultural helping network (odds ratio (OR) = 1.70, $p = 0.01$), and higher yields (metric tons ha^{-1} ; OR = 1.84 $p = 0.05$). Conversely, households that had lower odds of ranking 2021 as a bad year had an economic portfolio that included honey production (OR = 0.17, $p = .01$). Both economic diversity (OR = 0.49, $p = 0.09$) and number of external ties (OR = 0.94, $p = 0.07$) were suggestive of lowering the odds of ranking 2021 as a bad year, with the effects approaching significance. Sensitivity analysis using both model selection and imputed data (electronic supplementary material, tables S5 and S6), show qualitatively similar results.

Together model results suggest that families that are socially and economically more diversified tend to perceive 2021 as a normal or good year, while those that are more vested in agricultural intensification, perceived it as a bad year.

5. Discussion

Our analyses examined how climate and market forces shape farmers' assessments of harvest outcomes, and what household characteristics are associated with a good or bad harvest year. The results lead to several points about small-scale farmers who are transitioning from a subsistence to a market-integrated economy.

First, most households concur in their assessment of harvest outcomes, with the greatest consensus when years are normal-to-good, suggesting that the community as a whole is exposed to similar background environmental and market factors. Second, explanations for the causes of bad and good years include both climate and market effects, with greater weight given to market effects during bad years. Of reasons given for harvest outcomes in 2021, which most farmers assess as a bad year, 4.7% of households mentioned climate factors only, 38.7% mentioned market inputs and climate factors and 46.2% identified market inputs only (electronic supplementary material, table S3). Low-quality fertilizer was a reason given for the bad year in 86% of household responses, a cause of poor harvests not identified in previous household surveys.

In the past, before the road, Maya farmers had clear-cut and consistent ideas about what they considered to be good, bad, normal years: a poor harvest was one that produced less than 1.5 metric tons per hectare, a normal harvest, 2–4 metric tons per hectare and a good harvest, greater than 4 metric tons per hectare. As farmers rely more on agricultural inputs, an extra layer of conditions is added to achieve a successful harvest. Said another way, 'fertilizer that doesn't work is as

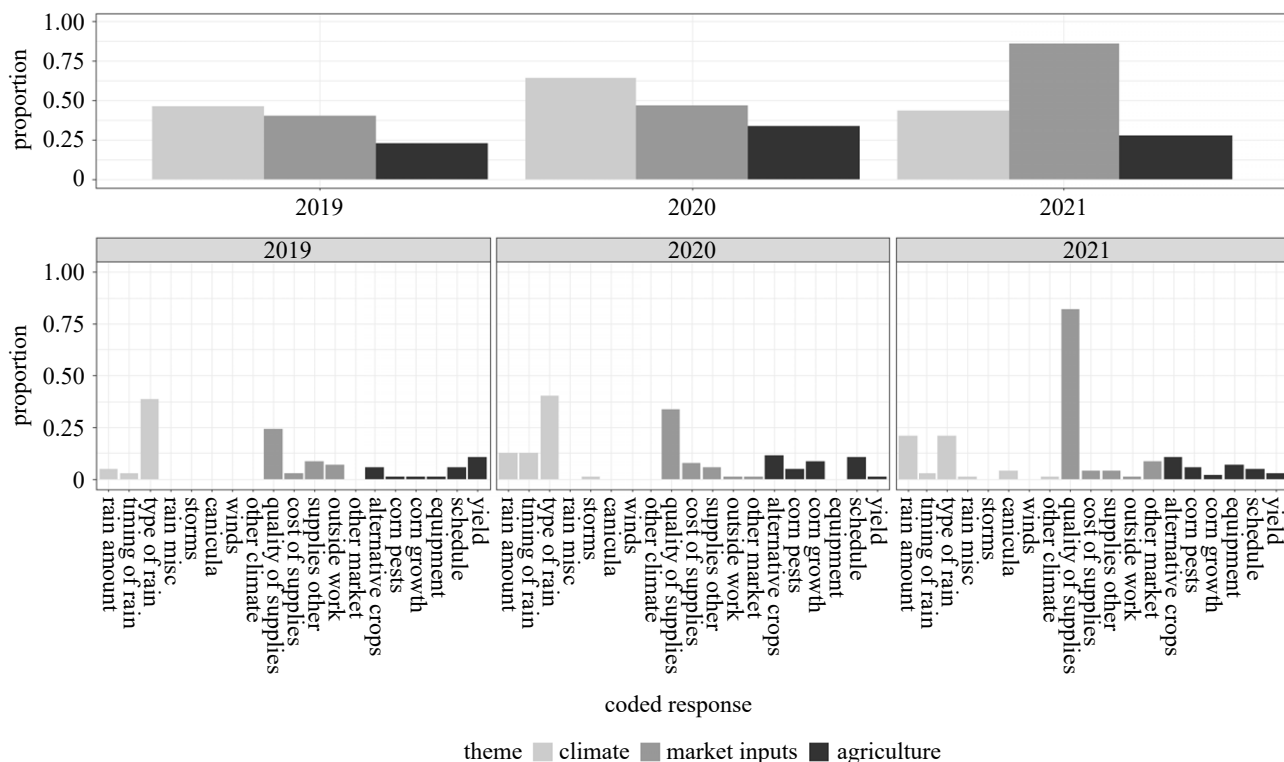


Figure 2. Proportion of open-ended responses explaining yearly assessments by coded category.

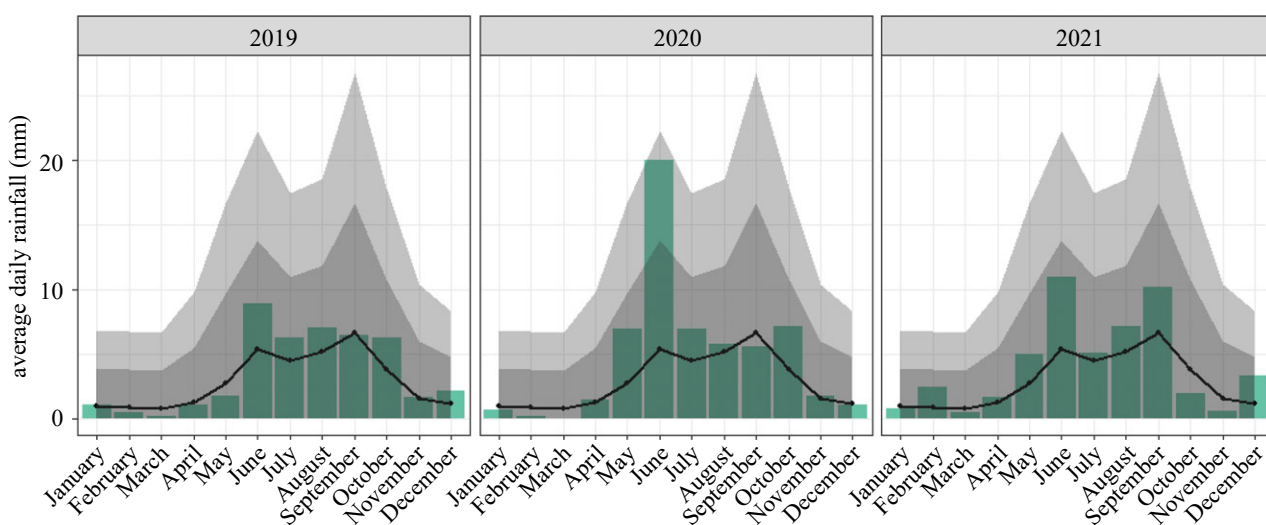


Figure 3. Average daily rainfall by month¹ (bars), showing historic baseline² (black line) and 1+ and 2+ standard deviations from baseline (shaded areas). Historic baseline and standard deviations precipitation data are taken from weather stations in close proximity to the study community and have continuous data from the 1950s through to December 2021 (<https://smn.conagua.gob.mx/es/climatologia/informacion-climatologica/informacion-estadistica-climatologica>). See text for more detail.

damaging as rain that doesn't come'. While the year 2021 has the climate characteristics (a pronounced canícula and heavy late growing season rains) that we have previously found to be associated with lower than normal harvests [47], this precipitation pattern is within the range of variation that traditional strategies can manage. Because farmers overwhelmingly point to market inputs as the cause of the poor harvest, it suggests that market factors are distinct from climate factors in constraining outcomes in new systemic ways that may strain extant backup strategies.

This contributes to the third finding that two divergent livelihood strategies are emerging with market integration, where households favour different economic strategies along a continuum of diversifying or intensifying. These

decisions in turn affect how the causes of harvest outcomes are perceived. Building a road into the community in 2003 initiated engagement in the regional economy and new ways to generate cash through crop sales and wage labour. Some households are responding to these first-time income producing opportunities by intensifying maize production. Other households are expanding their subsistence base, either by diversifying the variety of agricultural goods they produce (honey, cultivating peanuts or squash for seed), or by having family members pursue different subsistence activities (e.g. wage labour, craft production).

Model variables that signify agricultural intensification (more alters named as helping in the fields, greater returns per hectare) are associated with households that are more

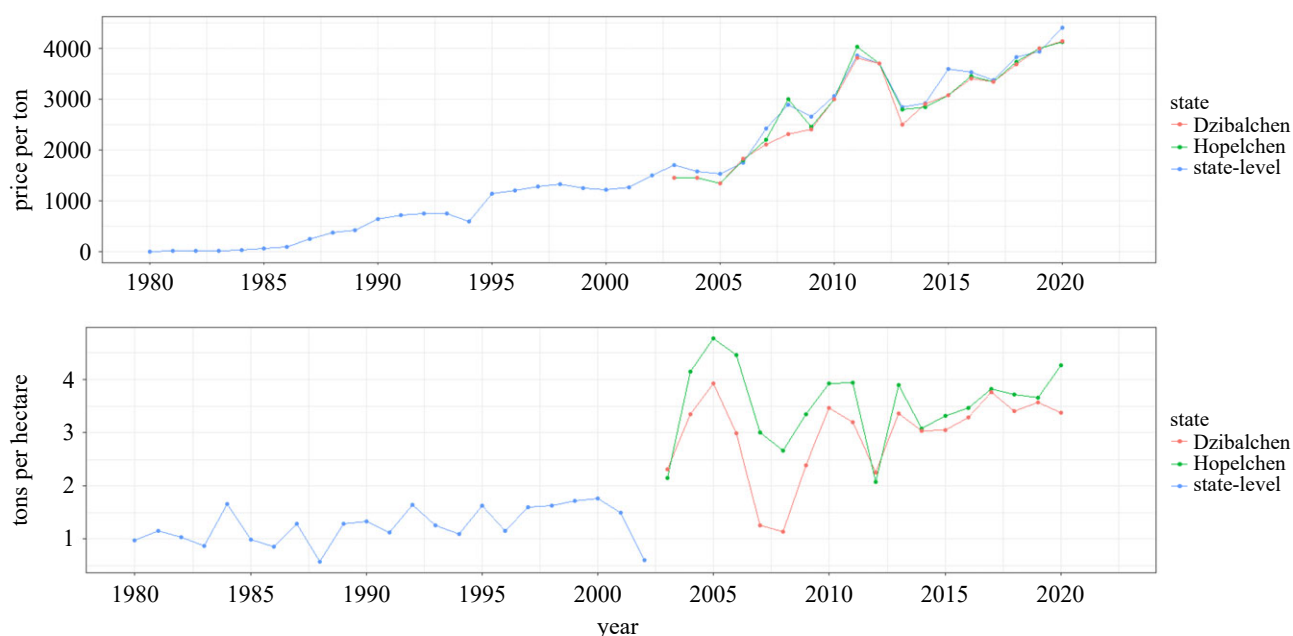


Figure 4. Historic maize prices (MX\$ metric ton⁻¹) and yield (metric ton ha⁻¹) based on municipal data (how selected), shown for the state of Campeche and for two subdistricts within Hopelchen municipality http://infosiap.siap.gob.mx/gobmx/datosAbiertos_a.php.

Table 2. Descriptive statistics of model predictors (see text for variable description).

variable	mean	s.d.
social resources		
household size	5.43	2.77
degree centrality	4.12	2.25
external alters	16.19	12.85
economic resources		
maize production per hectare	1.49	1.17
government subsidies (<i>per capita</i>)	7091.336	5381.894
economic diversity	3.37	0.98
honey production ^a	0.47	0.50
agricultural diversity	0.37	0.49
household demographic composition		
established household	0.81	0.39
age of household	48.68	14.30
bad year ^a	0.71	0.46

^aVariable is a binary (0,1) so mean is a proportion.

likely to rank 2021 as a bad year (table 2). While this seems counterintuitive, we interpret this result to indicate that market performance now shapes perceptions of bad years such that the more vested a household is in intensifying agriculture, the more pronounced their expectations are to have high yields and profits sufficient to repay loans. By contrast, economic diversity appears to diffuse those expectations. Model variables that are linked to economic diversity (honey production, agricultural diversification and expanded social networks) appear to have a protective effect in reducing the prospect of experiencing a bad harvest year. Thus, households that are broadening their economic base, appear to be more likely to perceive 2021 as a normal or good

year, while those more committed to maize intensification perceive it as a bad year.

(a) Building on traditional strategies and knowledge: policy implications

Because their livelihoods are directly tied to food production, small-scale farmers are some of the most vulnerable populations to climate change. This is coupled with the novel forces of market integration [7–9]. The Maya study offers several practical insights to mediate these impacts.

(i) Diversity and flexibility characterize traditional fallback strategies

The metaphor of double exposure reifies how market integration and climate change may perturb many aspects of wellbeing. Long-term interview and economic data show that the Maya have several traditional strategies to reduce the risk of crop failure and shortfalls in food production. They plant in different locations to offset geographically patchy rainfall (both too much and too little). They stagger when they plant across the growing season to mediate the possibility of a delayed or prolonged *canícula*. They put more land under cultivation than they need for domestic consumption to store as a backup should the next year's crop underperform, and they store maize in different locations.

Our results suggest that they build on these diverse strategies, both socially and economically, to navigate a more secure place in a changing, market integrating world (also see [6,7]). Specifically, we tested whether household size, the breadth of social network ties within and outside the community, and economic diversity are associated with experiencing a bad year. We found that households that (i) maintain strong local networks while also developing outward looking social connections, (ii) have access to institutional support, and (iii) have economically diverse portfolios are more buffered from experiencing a year as bad. This adds to a previous finding that more economically diverse Maya households—those

Table 3. Logistic regression predicting household experience with a bad year. (Values in bold indicate significance at the $p < 0.05$ level.)

	odds ratio	coef	s.e.	p-value
intercept	5.75	1.75	2.13	0.41
social resources				
household size	1.01	0.01	0.13	0.92
degree	1.70	0.53	0.20	0.01
external network ties	0.94	−0.07	0.04	0.07
economic resources				
metric tons per hectare	1.84	0.61	0.31	0.05
government subsidies <i>per capita</i>	1.00	0.00	0.00	0.35
economic diversity	0.49	−0.71	0.42	0.09
honey producer	0.17	−1.78	0.69	0.01
agricultural diversity	1.44	0.37	0.72	0.61
household demographic composition				
age of household head	1.00	0.00	0.02	0.91
established household	0.81	−0.21	0.91	0.82
model fit				
<i>n</i> observations	87			
pseudo R^2	0.24			
Akaike information criterion	93.30			

that maintain both a firm agricultural base, while also engaging in some alternate means to generate cash—have a higher income *per capita* [35], suggesting that diversification is protective to some measure.

(ii) Intensification and market forces constrain strategies to cope with climate variation

Our aim was to assess whether climate and/or market forces guide farmers' perceptions of livelihood outcomes. We find that both climate and market forces are identified as causes of bad harvests, but that the latter carries greater weight in poor harvest years. Distinguishing these effects is significant to maintain a point on climate change and to implement interventions that consider the implications that market effects have on livelihoods.

We find that in the transition from subsistence farming to market production, traditional strategies that were effective in mitigating climate variation, become strained. Reliance on market inputs forges a more rigid food production system, which conflicts with the diversity and flexibility on which traditional strategies depend. For example, prior to access to agricultural inputs, seed for indigenous maize varieties was conserved from the harvest, and planted the following year. Seed for the new hybrid varieties, however, must be purchased each year to breed true. Farmers remark that if they use hybridized seed conserved from the previous year, germination rates are poor, yields are low and the maize does not

have the characteristics that make it marketable (seed companies also penalize farmers who use seed from previous years, rather than purchasing it). Further, because the distribution of maize seed to farmers is now controlled by companies or the government, the window in which farmers can plant is driven by delivery schedules, rather than their own assessment of when precipitation conditions are favourable to plant. One of the most consistent comments farmers make is that they receive their seed too late to work around the timing of the *canícula* and late growing season storms. The best policy change would be one that ensures farmers are not handicapped by delayed seed deliveries, and have the flexibility to make their own informed decisions about when it is most optimal to plant.

In another example, the high-water content of new hybrid maize varieties limits its storability to a few months, restricting how prepared farmers can be for a bad harvest year. This short shelf life, and reliance on credit to purchase agricultural inputs, means farmers have a narrow time frame in which to sell their surplus and repay debts, constraining in their ability to respond to fluctuations in the price of corn. While the best price for maize may be in spring, lenders may not be willing to wait.

Additionally, intensifying maize production entails the use of tractors and fertilizers, which also limits the ability of traditional strategies to manage climate variability. Tractors are restricted to the large, flat savannahs and cannot access the more nutrient rich slopes. As such, the traditional spatial hedge betting strategy to cultivate in a variety of ecozones has become limited. As a compounding effect, the soils in the savannahs, are becoming depleted, increasing reliance on fertilizer, which in turn renders Maya farmers vulnerable to global economic events. The Russian-Ukraine war, for example, exacerbated a global fertilizer shortage, increasing its price [49,50] and reducing the variety of products. The poor quality of fertilizer is a considerable concern for nearly every farmer in the community. One brand of fertilizer is on offer through government subsidies, and the lack of competition likely intensifies problems with quality, limiting their ability to choose.

Each of these examples points to ways in which market inputs are creating a more rigid food production system by tightening planting and harvesting schedules, limiting choices and instituting checks on what was a set of diverse and flexible strategies to cope with climate variation.

(b) Scale matters

Climate scientists, social scientists, archaeologists and anthropologists approach climate change from different perspectives and consequently often view these events and consequences at different scales. Of the plethora of climate data available, which are most relevant to capture climate change effects? People living in small-scale societies offer pertinent insights into answering this question. We have found that coarse-grained climate data (e.g. annual averages, regional and national averages) miss what is critical to the people making their living close to the environment [47]. Specific to the Yucatan Peninsula and Maya farmers, coarse-grained patterns conceal seasonal patterns (the *canícula* and late growing season rainfall), and the very information that farmers tell us most directly affects their food production. Maya smallholder

farmers also have been clear that market inputs are a key determinant of poor yields.

This study integrates small-scale society research into the larger climate science literature by using a much-needed, bottom-up, detailed, individual and quantitative account of how smallholder farmers locally respond to climate change [51], and the double exposure of its relationship with market dynamics. This approach contributes to climate change research by inverting more common methodologies, which uncover signature changes in climate data, and then make inferences about effects on human behaviour.

6. Conclusion

The transition from a subsistence to a market economy often is seen as one system replacing the other. However, mixed economies, with diversification at their centre, can be stable and long-term strategies, as evidenced archaeologically, historically and contemporarily [11,15,52]. Rather than a top-down approach to implementing policy, we emphasize the need to first determine how people on the ground perceive the climate and market effects that are pertinent to their livelihoods. The point has been well made that traditional ecological knowledge (also referred to as Indigenous and local knowledge) is challenged to keep pace with changes brought about by climate change and globalization [53,54]. The Maya appear to be astute stewards of climate knowledge, and have effective social and economic strategies to manage climate variation and potential food shortfalls. We highlight that as small-scale societies move towards greater reliance on the labour market, the best protection against the double exposure are policies that do not thwart their ability to diversify or flexibly respond to expected climate fluctuations, and encourage mixed economies to thrive.

Ethics. The household social, economic and agricultural data collected in 2021 was approved by the University of Utah Institutional Review Board IRB no. 00140260. Verbal consent was obtained from all subjects. Written consent is inappropriate in this cultural context because many individuals have never signed a document, and we do not wish participants to become accustomed to signing documents that they themselves cannot read. Project aims and protocols are explained in a consent script first to community comisarios, and leaders, and then to individual participants.

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Data accessibility. We draw climate data from publicly available database of weather stations in the state of Campeche, Mexico years (accessible through the government's website: <https://smn.conagua.gob.mx/es/climatologia/informacion-climatologica/informacion-estadistica-climatologica>). To contextualize the market environment in which rural Maya farmers are operating, we utilize government published reports for non-irrigated maize yields and the market price of maize for the rural municipality (a ~7500 km² area) in which the study community is located (database available since 2003 for rainfed maize at: http://infosiap.siap.gob.mx/gobmx/datosAbiertos_a.php). Our research protocols involve capturing detailed qualitative descriptions of what features of climate variation are most relevant to Mayan farmers as well as their social and economic responses (see supplementary material Table S1, S7).

Additional information and data are provided in the electronic supplementary material [55].

Declaration of AI use. We have not used AI-assisted technologies in creating this article.

Authors' contributions. K.L.K.: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, writing—original draft, writing—review and editing; J.V.H.: conceptualization, formal analysis, funding acquisition, investigation, methodology, supervision, writing—original draft, writing—review and editing.

Both authors gave final approval for publication and agreed to be held accountable for the work performed therein.

Conflict of interest declaration. We declare we have no competing interests.

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Endnotes

¹Monthly average of daily precipitation for each of three years.

²The black line indicates the monthly average of daily precipitation averaged across the 60 years of data across four local weather stations. The grey shaded area is the +1 s.d. and +2 s.d. from the mean.

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