frontiers
in Sustainable Food Systems

ORIGINAL RESEARCH
published: 06 April 2021
doi: 10.3389/fsufs.2021.618453

Mayan Traditional Knowledge on Weather Forecasting: Who Contributes to Whom in Coping With Climate Change?

Tania Carolina Camacho-Villa[1*†]*, Tania Eulalia Martinez-Cruz*[2]*, Alejandro Ramírez-López*[1]*, Matias Hoil-Tzuc*[1] *and Silvia Terán-Contreras*[3]

[1] *Socioeconomics Program, International Maize and Wheat Improvement Center, Texcoco, Mexico,* [2] *Livelihoods and Institutions Department, Natural Resources Institute, University of Greenwich, Chatham, United Kingdom,* [3] *Patrimonio Cultural, Secretaria de la Cultura y las Artes, Mérida, Mexico*

OPEN ACCESS

Edited by:
Helda Morales,
The South Border College (ECOSUR), Mexico

Reviewed by:
Stewart Diemont,
SUNY College of Environmental Science and Forestry, United States
Ana Isabel Moreno-Calles,
Universidad Nacional Autónoma de México, Mexico

***Correspondence:**
Tania Carolina Camacho-Villa
CCamachoVilla@lincoln.ac.uk

†Present address:
Tania Carolina Camacho-Villa,
Lincoln Institute for Agri-Food Technology, University of Lincoln, Lincoln, United Kingdom

Specialty section:
This article was submitted to Agroecology and Ecosystem Services, a section of the journal Frontiers in Sustainable Food Systems

Received: *09 November 2020*
Accepted: *15 February 2021*
Published: *06 April 2021*

Citation:
Camacho-Villa TC, Martinez-Cruz TE, Ramírez-López A, Hoil-Tzuc M and Terán-Contreras S (2021) Mayan Traditional Knowledge on Weather Forecasting: Who Contributes to Whom in Coping With Climate Change?
Front. Sustain. Food Syst. 5:618453.
doi: 10.3389/fsufs.2021.618453

Despite international commitments to integrate indigenous peoples and their Traditional Ecological Knowledge (TEK) in actions combating climate change, their inclusion remains limited. Integrating TEK with scientific knowledge has become particularly important in sectors such as agriculture, which both contributes to and is affected by climate change. While there is a general recognition that integrating TEK will contribute to climate change adaptation, agricultural interventions have made little progress in achieving this due to the assumption of a clear divide between TEK and scientific knowledge. This paper considers that knowledge integration is already occurring, but in contexts of economic, sociocultural, and political inequalities. We elaborate on the case of traditional weather forecasting methods used by Mayan indigenous farmers in Mexico's Yucatán Peninsula to propose a social justice perspective for knowledge integration in climate change interventions. Using information from three studies conducted between 2016 and 2019, we first explain the importance of weather and traditional weather forecast methods for indigenous Mayan farmers. Later we describe in detail both these methods and their links with Mayan cosmology. Findings show how weather phenomena such as drought and hurricanes are main concerns for milpa farming. They illustrate the diversity of traditional short, medium, and long-term weather forecast methods based on observations from nature and the sky. Farmers also perform rituals that are related to their Mayan gods and goddess. As TEK not only defines agricultural calendars but also reproduces Mayan culture, we discuss what is needed for its integration into actions combating climate change. We use a rights-based approach that considers the economic, cultural, and political scales of justice to equally allocate resources and benefits for traditional knowledge systems, recognize indigenous values and worldviews avoiding cultural harms, and accomplish indigenous self-determination through equal representation. As a result, we hope to incentivize development actors engaged in agricultural interventions on climate change to critically reflect and examine power dynamics and relations when working with indigenous communities.

Keywords: traditional weather forecasting, traditional ecological knowledge, Mayan rain cosmology, climate change, milpa, Yucatán Peninsula, social justice

INTRODUCTION

Indigenous peoples and their Traditional Ecological Knowledge (TEK) on weather have been considered essential in global efforts to combat climate change. While indigenous peoples represent just 5% of the world's population, they inhabit 22% of the Earth's surface and are custodians for 80% of the planet's biodiversity (ILO, 2017). There is evidence that their land management systems ensure sustainability; their farming practices minimize emissions from deforestation; and that their adaptation strategies can be used in coping with climate variability (Macchi et al., 2008). Yet, this TEK—and the resource-based livelihoods of indigenous communities—are themselves threatened by climate variability and extreme environmental events (Nakashima et al., 2012; Mafongoya and Ajayi, 2017).

International commitments for engaging indigenous communities began with the Indigenous and Tribal Peoples Convention, 1989 (No. 169), which provides a framework for ensuring indigenous peoples' consultation and participation in decision-making. Moreover, the Intergovernmental Panel on Climate Change and agreements like the Cancun Adaptation Framework and the Paris Agreement/COP21 recognize the invaluable role of TEK in developing climate change adaptation strategies (Nakashima et al., 2012; Mafongoya and Ajayi, 2017) and the need to integrate it with scientific knowledge.

Integrating TEK and scientific knowledge is especially important in agriculture (FAO, 2013). Crop/livestock practices and deforestation account for almost 25% of global greenhouse gas emissions (World Bank, 2018) while, at the same time, increased climate variability exacerbates production risks and challenges farmers' resilience (Lipper et al., 2014). Various approaches attempt to integrate TEK and scientific knowledge to both mitigate and adapt to climate change (Cameron, 2012), from those promoting scientific validation of TEK (Hiwasaki et al., 2014) to others advocating for the sustainability and resilience of TEK (Nair et al., 2017; Singh and Singh, 2017). As yet, these efforts have failed to integrate TEK because they assume a clear divide between TEK and scientific knowledge that becomes problematic in agricultural interventions. This paper attempts to overcome the dichotomy of TEK vs. scientific knowledge by recognizing the dynamic and interactive nature of both knowledge systems (Agrawal, 1995). We consider that both types of knowledge are situated (Haraway, 1988) as they are tied to specific identities. This leads us to not only ask the question of "what knowledge" but also of "whose knowledge"; who is leading the process of knowledge generation and who is benefitting from knowledge utilization are important questions to reflect on. The contexts and processes in which different type of knowledge interact also become relevant.

For the case of weather forecasting knowledge, this means moving away from the narrative of a single evolutionary pathway from antique astronomic and nature/sky based forecasts to modern numeric and probabilistic predictors to recognize that nowadays these different methods interact to predict climate futures, characterized by high levels of uncertainty (Makridakis, 1986; Cabañas, 2014). It also requires an acknowledgment that both TEK and scientific knowledge weather forecasting share methodological challenges of consistency and quality, as well as practical challenges of value for end users (Murphy, 1993) that brings in questions associated with equity (Lemos and Dilling, 2007). Questions on equity, social equality, inclusion, power relations, and social justice have been discussed in the context of climate change in agriculture by Chandra et al. (2017), Karlsson et al. (2017) Newell and Taylor (2018), and Budiman (2019). We consider all these questions in our proposal to integrate indigenous peoples and their TEK into efforts to combat climate change with a social justice perspective.

We focus on a social justice perspective for three primary reasons. The first is that justice has long been a part of discussions around climate change, with existing concepts like environmental justice and climate justice. The second is that environmental and climate justice have been used by different stakeholders such as scholars elaborating ideal theories, elite non-governmental organizations proposing pragmatic policies, and grassroots movements expressing social concerns (Schlosberg and Collins, 2014). Third, we considered that a social justice perspective allows advancement from a utilitarian view of traditional knowledge toward a rights-based perspective that considers the people who hold the knowledge, i.e., Indigenous peoples.

We used the framework of Fraser (2010), which outlines three dimensions ("scales") of justice used by indigenous movements to make claims about climate change. One of these dimensions, "distributional justice," refers to the fair sharing of benefits and costs in mitigating climate change, e.g., by reducing CO_2 emissions (Budiman, 2019). It also considers indigenous people's claims on their marginality due to colonialism and globalization (Doolittle, 2010). The second dimension of justice claimed by indigenous movements relates to their political representation as "rights-holders" to participate in national or international decisions on climate change action (Tsosie, 2007; Borras Pentinat, 2016). This is also associated with their self-determination claims in decision-making processes that affect them, with governance frameworks like "free prior and informed consent" (Schlosberg and Collins, 2014; Ludwig and Macnaghten, 2019). The third dimension is recognition, which considers indigenous people's relationship with nature as part of their identities, livelihoods, and the bioculturality of their natural resources—which is usually neglected in development interventions. For indigenous people, their culture is inseparable from the conditions affecting their territories, thus climate change also causes cultural harms as it affects their ability to reproduce their traditions, rituals, and cosmologies (Tsosie, 2007; Schlosberg and Caruthers, 2010). Cultural harm also includes affecting indigenous worldview (Samaddar, 2006; Eriksen et al., 2019) that explain indigenous people climate change adaptation and resilience capacities.

We apply Fraser's (2010) scales of justice in this study to propose alternative paths for integrating indigenous people and their knowledge in mitigating and adapting to climate change. Our contribution to a rich, existing literature on this topic (Tsosie, 2007; Schlosberg and Caruthers, 2010; Borras Pentinat, 2016; Chandra et al., 2017) is based on empirical findings linking farming activities to the weather forecasting methods used by Mayan indigenous groups who live in the Yucatán

Peninsula of Mexico. Weather forecasting has long been a crucial component of agriculture and has developed into a rich body of traditional knowledge in Africa (Jiri et al., 2016), Asia (Galacgac and Balisacan, 2001; Acharya, 2011), Europe (Fuentes Blanc and Fuentes Blanc, 2003) and the Americas (Albores and Broda, 1997; Orlove et al., 2002). While weather forecasts are a crucial part of early warning and adaptation actions to combat climate change, they also make an important contribution to mitigation by influencing agricultural calendars and cultivation practices. It is estimated that weather forecasting is used to define the start of the agricultural cycle for 72% of land cultivated under rainfed conditions worldwide (Molden, 2013). Moreover, it becomes determinant to define farmers' plans with respect to the moments and the ways in which cultivation practices will take place. The appearance and use of scientific weather forecasts starting from the seventeenth century has not superseded the use of traditional forecasting methods. This is especially true for indigenous farmers around the world, who continue to rely on their traditional weather forecasting methods. In this paper, we aim to shed light on the role of TEK in agricultural weather forecasting, as an alternative to current dominant approaches. We investigate how TEK can play an important role in coping with climate change and fostering resilience in the face of extreme environmental events. Our goal is to broaden the discussion of alternative paradigms to combat climate change and contribute to the reclamation of the role of TEK as an inherent right of indigenous peoples.

We chose to focus on the case of a Mayan indigenous group who live and farm the milpa farming system in the Yucatán Peninsula, Mexico for several reasons. Firstly, Mexico has been identified as particularly vulnerable to the impacts of global climate change, especially in agriculture due to increased temperatures and decreases in rainfall (FAO-SAGARPA, 2014). Secondly, scenarios predict that extreme climate events in the next few years—such as hurricanes, floods, and droughts—will cause total agricultural production losses in localities of the Yucatán Peninsula (FAO-SAGARPA, 2014). In response, Mexico has played a leading role in international negotiations and has advanced its national policies, laws, and strategies on climate change (SEMARNAT-INECC, 2016). Concrete actions to mitigate climate change include a regional commission, a regional strategy, state programs, and projects such as REDD+ (CCPY http://www.ccpy.gob.mx/). Most of these actions focus on tropical forests where Mayan indigenous people have lived and farm for millennia. Yucatán Peninsula is the area where this group concentrates with around 800,000 persons (INEGI, 2005). The history of this indigenous group (the second biggest in Mexico; INEGI, 2015), dates to the Lowland Maya civilization that inhabited this region until its collapse during the ninth to eleventh century. Most scholars consider that this collapse occurred due to severe droughts and extreme climate fluctuations (Douglas et al., 2016; Smyth et al., 2017; Ebert et al., 2019). Weather has thus shaped the long history of the Mayan indigenous group. This is reflected in their rich TEK, which can be traced to pre-Columbian documents like the Maya Agricultural Almanac (Milbrath, 2016). Current Mayan milpa farming system has been shaped by weather variation, leading to crop diversification that is an important Mayan livelihood strategies (Terán-Contreras and Rasmussen, 1995, 2008b). Although this pre-Columbian farming system has been extensively studied, it has been defined in different ways (Rodríguez-Robayo et al., 2020) as it simultaneously produces food, represents an integral approach of tropical forest management, and reproduces Mayan culture (Terán-Contreras and Rasmussen, 1995; Fedick et al., 2003; Martín-Castillo, 2016). The wide recognition and documentation indicating that milpa TEK represents the Mayan cosmological and ecological paradigm and the backbone of Mayan livelihood strategies (Konrad, 2003), is not necessary reflected in regional actions to combat climate change.

THE HISTORICAL IMPORTANCE OF WEATHER FOR MAYAN PEOPLE OF THE YUCATÁN PENINSULA

The Yucatán lowland region is characterized by a limestone bedrock that determines the karst terrain dominated by a low and relatively flat plain of porous limestone with little soil (Vázquez-Domínguez and Arita, 2010). Due to the type of soil, surface water (in the form of small lakes and rivers) is confined to the southern part of the peninsula. In the north, all water reservoirs are underground, and the karst terrain generates many *cenotes* (water-filled sinkholes) (Vázquez-Domínguez and Arita, 2010). This region has a tropical climate characterized by two distinctive seasons: rainy (May to November) and dry (December to April) (Islebe et al., 2018). Rainfall is spatially distributed; the northwest part of the peninsula typically receives just 500 mm of rain, while in the southeast it can reach 1,200 mm (Terán-Contreras and Rasmussen, 2008a). The region's proximity to the Tropic of Cancer and the influence of the Atlantic Bermuda-Azores anticyclone, together with the effect of trade winds and the influence of tropical perturbations, allow the formation of hurricanes (Vázquez-Domínguez and Arita, 2010). Because its geographic location and the morphologic characteristic, the peninsula is hit harder, and with higher frequency than other areas by hurricanes, tropical storms, and winter precipitations (locally known as *nortes*). These events, together with rainfall variation that can cause partial or total harvest losses, have always generated concerns for the milpa system (Campos-Goenaga, 2012).

The rich literature of archeology and paleoclimate studies on the Mayan Collapse indicates that this pre-Columbian civilization suffered several episodes of drought in different periods. Ebert et al. (2019) conclude that droughts during the Late pre-Classic Period were negated by a broad subsistence strategy that helped to absorb shocks to maize-based production. These authors also propose that the Mayan collapse during the Late Classic Period occurred due to a mix of severe floods and droughts, combined with changes to diet and food preferences. Other authors like Dahlin et al. (2005) propose explanations such as the presence of hurricanes every 8–9 years. Douglas et al. (2016) refer to complex economic and political processes that, together with climatic instability during the eighth century, contributed to societal disintegration in the eleventh century.

There is evidence of the knowledge of pre-Colombian Mayan people on weather forecasting for agricultural cycles (Sharer and Traxler, 2005). Calendars like the *Tzolkin* or Moon Calendar of 260 days and the *Haab* or Sun Calendar of 365 days were central to the milpa system as they defined the dates of cultivation practices and rituals (Romero Conde, 1994; Valencia-Rivera, 2017). Astronomy and mathematics were used by Mayan priests to define the start of the agricultural rainy season based on eclipses and Venus' closeness to the Pleiades, as illustrated in the Agricultural Almanac of the Madrid Codex (Milbrath, 2016). The appearance of *Chaak* (the god of rain and hurricanes) in this codex sowing maize with the *xuul* (stick) still used by Mayan farmers today (Morales-Damián, 2017) demonstrates how this deity has survived until today[1]. Rain was, and continues to be, a fundamental part of Maya religious practices as "a symbol of fertility, a phenomenon that people actively sought to control through religious practice and as a fundamental building block of Maya universe encompassing the natural and divine elements of the universe" (Dao, 2011). Rituals and forecasting were part of the coping strategies for weather, an element humans do not control thus they worship and ask to those who do (Deities) (Smyth et al., 2017).

The importance of weather is also evident in later periods of the Maya regional history. During the Colonial period (1519–1821), periods of extended drought occurred together with natural events (such as locus infestations), social phenomenon (such as epidemics and warfare), and top-down policies for the storage and acquisition of staple foods, leading to agricultural disasters and famines that affected regional population dynamics (Hoggarth et al., 2017). The new social arrangements affected not only the strategies used by Maya farmers to cope with weather, but also the food, agricultural production, and indigenous knowledge systems more generally (Fisher, 2020). The colonial relation was characterized by an asymmetrical social contract in which the Spanish Colony received maize taxes (tributes) and free laborers from the Mayan agrarian society and, in exchange, the Mayan Society retained control to important assets like land, water, and forests (Campos-Goenaga, 2012). Tributes were not new in the Mayan Society, where autonomous provinces governed by local elites collected them and labor services from the people living in their settlements. However, the way those tributes were implemented reflects what Fisher (2020) called the change between political leadership that worked with farmers' TEK, vs. political leadership that worked against it. That was the case of maize tax calculation from harvested maize to an estimation based on the planted area. This is also expressed by the Colonial government imposition to create spatially discrete and stable towns and obligated farming around them. This contrasted with the more decentralized and nomadic approach before the Colonial period that considered the ecological conditions and spatial distribution of risk (Terán-Contreras and Rasmussen, 1995; Mariaca Méndez, 2015; Fisher, 2020). The concentration of people and plots around towns increased their vulnerability as nearby lands were not necessarily fertile and a lack or variation in rainfall would affect more people across a smaller area of land (Mariaca Méndez, 2015). Rituality and forecasting, led by traditional Mayan priests continued to play a key role for Mayan farmers who participated in as "without rain there is no maize and without maize there is no life" (Love, 2011). Colonial chroniclers like de Landa (1959) referred to collective celebrations led by these Mayan priests where the year forecast for the next agricultural cycle was presented and discussed together with other ceremonies and rituals.

Weather and social events continued to shape the history of the Yucatán peninsula throughout the Independent period (from 1821 until now). One important consideration of this period is that it did not necessarily change the neo-colonial relation between local elites and indigenous Maya communities (Frischmann, 2001). For some historians, the nineteenth century represented a step back with respect to indigenous rights and explained the appearance of indigenous rebellion. The Caste War of 1847 to 1901, for example, was an agrarian rebellion of Maya indigenous people against local elites who privatized their communal land, exploited their labor on large sugarcane, cotton, and livestock estates, and desired to change their agricultural production systems (Joseph, 1985). Prophecies of this rebellion were expressions of the Mayan prediction tradition in a century in which people stopped using the Mayan Calendars (Bracamontes-Sosa, 2009). Critical moments of this war were defined by the weather. In 1848 Mayan rebels broke the siege of Merida city due to the start of the rainy season that define the start of their milpa planting (Reed, 2001; Paoli Bolio, 2017). While the Agrarian Mexican Revolution during the first half of the twenty-century distributed land and gave legal rights to peasants and indigenous communities, the processes of modernization and neoliberal policy impacted indigenous peoples, who are currently among the poorest in this region.

The last century of Yucatán Peninsula history has been characterized by weather disasters. Hurricanes have hit in total 86 times (Gobierno del Estado Yucatan, 2014a). Droughts have also become more intense and prolonged, especially the *canícula* seasonal drought, which impacts small-scale farming (Metcalfe et al., 2020). Furthermore, irregular rain patterns and extreme temperatures are already affecting (and will likely continue to affect) the subsistence rainfed agriculture like milpa practiced mainly by the most vulnerable and poor, the Mayan indigenous people. Their vulnerability is not only due to climate change, but also to economic exploitation and social and political marginalization that has led to serious environmental degradation of their natural resources (Schneider and Haller, 2017). Regional governments and NGOs have received international and national support for combating climate change with projects such as REDD+. Although, these efforts count with robust assessment of the critical status and the key role of indigenous people and their TEK, they do not define concrete actions to ensure their inclusion in their different action programs (Gobierno de Quintana Roo, 2013; Gobierno del Estado Yucatan, 2014b; Secretaria de medio Ambiente y Aprovechamiento Sustentable, 2015).

[1]In contrast to the fate of other deities like *Itzamná* (responsible for superficial water), whose importance declined with the Mayan collapse and disappeared with the arrival of the conquerors and their new gods.

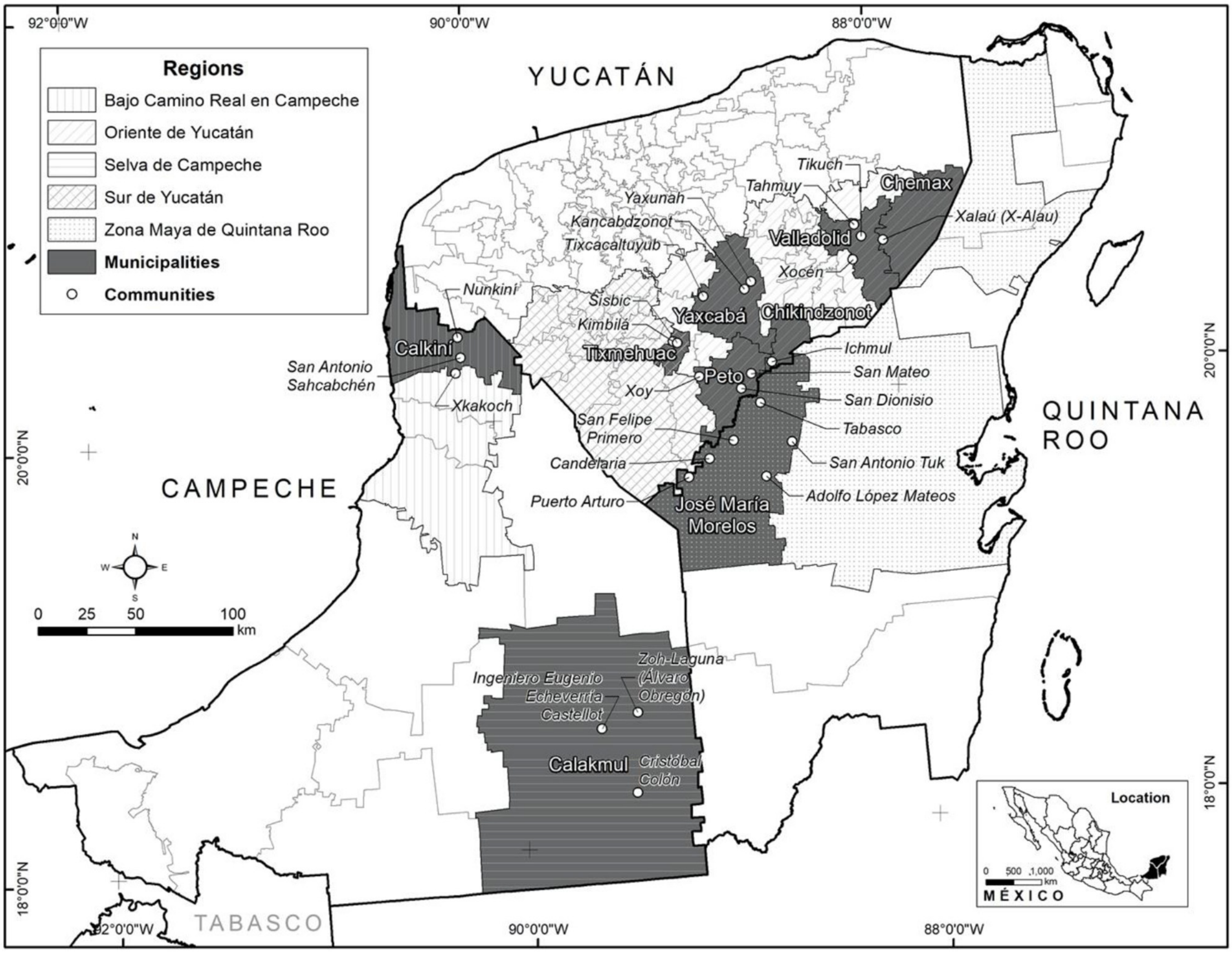

FIGURE 1 | Maps of the communities, municipalities, and regions where data was collected.

INFORMATION SOURCES AND ANALYSIS

This paper uses primary data complemented with secondary data from specialized literature. Primary data was gathered during 2016–2019 as part of the development project "*Modernización Sustentable de la Milpa en la Peninsula de Yucatán*" (Sustainable Modernization of the Milpa in Yucatán Peninsula) as part of authors involvement. This project implemented a methodology for co-designing, adapting, and deploying technologies to improve the milpa system by responding to regional challenges of crop productivity, biodiversity conservation, soil, and water management, and climate change. Secondary data sources were compiled from other studies in the Yucatán region and represent a robust literature on the Maya indigenous group, TEK, milpa system, and climate change.

Primary data was collected in 27 communities from 10 municipalities where milpa farming is prominent, across five regions of the Campeche, Quintana Roo, and Yucatán states of the Yucatán Peninsula (see **Figure 1**). Some municipalities (i.e., Calkini, José María Morelos, Calakmul, Chikindzonot; CONEVAL, 2015) are part of the national municipalities with the highest level of poverty. These regions illustrate the diversity of conditions under which the milpa system is practiced. The first region, *Oriente de Yucatan*[2] has traditionally been the maize producing region of the State. Maya communities cultivate milpa for consumption and generate income by migrating to the tourist region of Cancun, the industrial area around Merida City, or the cattle farms in the northern part of this state (Quinta et al., 2003). We collected data from farmers in communities of the municipalities of Yaxcabá, Valladolid, Chemax, Peto, and Chikindzonot. There have been more efforts to modernize agriculture in the second region, *Sur de Yucatán* (see text footnote 2). This is an area where Maya peasants have been able to conserve their agricultural traditions in the context of agricultural modernization and international emigration (Quinta et al., 2003). Data was collected in the municipalities of Tixméhuac.

[2]https://www.yucatan.gob.mx/estado/municipios.php

TABLE 1 | Sources of primary data.

Year	2016	2018	2019
Study	Baseline assessment	Evaluation of the sustainability of the milpa systems	Traditional knowledge on weather
Objective	To characterize milpa households and to discuss climate challenges	To assess the sustainability of milpa systems and their technological interventions	To document TEK on weather forecasting and cosmology around it
Methods	+Structured interview at household level +Group discussion at community level	+Semi-structured interview at household level +Group discussion at community level	+Open question survey to local experts on weather prediction and rituals +Workshop with different type of stakeholders on Weather
Participants	109 (14 women and 95 men)	104 (8 women and 96 men)	31 (1 woman and 30 men)
Coverage	6 localities in 3 municipalities	11 localities in 4 municipalities	15 localities in 5 municipalities
Type of data	Categorical and numerical data	Categorical and numerical data	Qualitative data
Analysis	Descriptive statistics using means and percentage Content analysis	Descriptive statistics using means and percentage Content analysis	Descriptive statistics using frequencies Content analysis

The third region is the municipality of José María Morelos in the *Zona Maya de Quintana Roo*[3], where settlements were established for rubber and tropical timber exploitation and because of the exile of the Caste War rebels (Barrera-Rojas and Reyes-Maya, 2013). While agriculture, livestock management, and apiculture are practiced, ecosystem services have also become a part of forest management activities in recent decades. The fourth region is known as *Bajo Camino Real en Campeche*[4]. It is an important commercial region that connects the Peninsula with the rest of Mexico. In this region the main activities are milpa farming for subsistence, horticulture for commercialization, handicraft making, and apiculture (Pat-Fernández et al., 2012). Although trade has brought modernization, Maya inhabitants conserve their rituals and ancestral ceremonies (Quinta et al., 2003). Data collection in this region focused on communities in the Calkini municipality. The fifth region is *Selva de Campeche*[5], which was colonized by people from the Yucatán State and other Mexican states like Chiapas in the twentieth century. This area presents various management systems, such as the subsistence milpa system, commercial agriculture, cattle, apiculture, and several conservation efforts due to the proximity of the Calakmul Biosphere Reserve. We collected data from communities in the Calakmul municipality.

Our findings are taken from three studies conducted as part of the *"Modernización Sustentable de la Milpa en la Peninsula de Yucatán"* project. All three studies comprised: (a) data collection in communities, mainly with farmers participating in the project; (b) events to present and discuss findings with participant farmers and communities; and (c) data analysis of descriptive statistics, using Excel for quantitative data, and content analysis for qualitative data using Maxqda. The studies are described further in subsequent paragraphs, with complementary details given in **Table 1**.

The first study was conducted in 2016 and comprised a baseline evaluation of the status of the milpa systems (and their main challenges) and a characterization of the households who were cultivating them. We conducted 109 semi-structured, household interviews with participant farmers and 6 focus group discussions at the community level. Semi-structured interviews gathered information on: (i) household family general data; (ii) household farming plots; iii) milpa and other crop farming systems; (iv) home-garden and livestock management; (iv) the role of milpa products in their diets; (v) factors affecting the milpa; (vi) soil and water management practices; and (vii) challenges and opportunities affecting the milpa system. Here we reference results obtained from sections v and vii of the semi-structured interviews using content analysis for qualitative information and descriptive statistics to analyze quantitative data after its codification. Focus groups were organized through an open invitation issued by local authorities to all people cultivating the milpa system. A maximum of 15 people (mostly adult and elder men) participated in each focus group to answer questions characterizing their milpa farming systems and identity common problems and possible solutions.

The second study took place in 2018 and assessed milpa system sustainability. We collaborated with experts from GIRA (Grupo Interdisciplinario de Tecnología Rural Apropiada A.C.) who use the Framework for Assessing the Sustainability of Natural Resource Management System (MESMIS, for its acronym in Spanish). MESMIS is a systemic, participatory, interdisciplinary, and flexible framework for defining and measuring sustainability that was developed and has been implemented in different parts of Mexico (López-Ridaura et al., 2000). It operates in a six-step cycle: (i) description of the management system; (ii) determination of critical points; (iii) selection of critical indicators; (iv) measurement of indicators; (v) presentation of results; and (vi) conclusion and recommendations (López-Ridaura et al., 2000). We used information collected during the fourth step using 54 semi-structured interviews at the household level and 4 focus groups

[3]http://www.inafed.gob.mx/work/enciclopedia/EMM23quintanaroo/regionalizacion.html
[4]https://es.wikipedia.org/wiki/Camino_Real_(Yucatán)
[5]http://www.inafed.gob.mx/work/enciclopedia/EMM04campeche/regionalizacion.html

at regional level with a total of 50 participants. Semi-structured interviews were used to measure indicators on sustainability attributes concerning milpa efficiency and vulnerability, and household risk management, inclusion, profitability, ecological quality, and market dependency. Findings reported in this paper are based on two open questions concerning weather forecast methods and were codified to transform them from qualitative to quantitative data. We used the focus groups to present and discuss results with the 54 participants and further discuss climate and traditional weather methods. We noted participants' comments and have used them as quotes in this manuscript.

As both studies indicated that weather was an important topic, in 2019, we undertook a third study on traditional knowledge on weather forecasting and the rituals around it. We used a qualitative survey that guided conversations with 31 local weather experts. These experts were identified using findings from previous studies and other project contacts, thus it was not a random sample. We also interviewed participating farmers and traditional Mayan priests known as *X'men* using an open question survey explored: (i) good and bad rainy season characteristics; (ii) traditional weather forecast methods; (iii) rain petition rituals; (iv) strategies to mitigate a bad rainy season; and (v) cloud taxonomy. The survey also created the opportunity to explore Mayan Cosmology specially because one of the authors is a Mayan Indigenous person who speaks the language fluently. We validated the information collected in a workshop that took place on May 9th, 2019. For this paper we used information from sections ii, iii, and v of the survey and undertook a content analysis of qualitative data to describe the weather forecast method. We also codified forecast methods to analysis their frequencies.

Informants were the household member in charge of milpa system. Most interviewees from the 27 communities self-identified as Mayas. While most interviewees were men (as in the 2016 study 87% respondents were men, in the 2018 study 93% and in the 2019 study 97% were men), women who are milpa farmers or worked together with their spouse also participated in the interviews. Informants were part of nuclear families with an average of 5 members. National and international emigration is relevant because some of the family members were migrants due to employment or education or marriage. Interviewees were mainly educated to elementary school level, though their children tended to have a high-school level education. Interviewees typically had diversified incomes, with 25% from governmental social protection programs, <25% from agricultural product sales, and the remainder from outside non-farm labor, local off-farm labor, livestock/forest products, and handicrafts. Communal land tenure is dominant across the communities, with very few exceptions of private property in Quintana Roo and the South Region of Yucatán State. Agricultural land is 97% rainfed with very little access to irrigation infrastructure. For interviewees milpa system becomes the spine of all their activities. This is the main activity to produce food and other crops that are important for the Mayan families not only to eat but also to sale. However, they recognize that their production has decreased threating their food supply due to the difficulty to access to production inputs, to the decrease of soil fertility and to weather conditions.

FINDINGS

Importance of Weather for Maya Indigenous Groups

There is rich literature that documents actual relevance of weather for Mayan communities and farmers associated to the impact of hurricanes and other tropical storms and floods (Faust, 2001; Alayón-Gamboa and Ku-Vera, 2011; Campos-Goenaga, 2012; Angelotti-Pasteur, 2014; Frappier et al., 2014), of droughts (Dahlin et al., 2005; Mardero et al., 2015; Estrada-Medina et al., 2016; Hoggarth et al., 2017), and to changes on rainfall patterns (Mardero et al., 2014; Ebel et al., 2018). In this section we look for contributing to this literature by elaborating in more detail on the different weather concerns.

Baseline interviews indicated a consensus that milpa production has decreased in recent decades due to challenges associated with weather (88% of interviewees cited drought and 18% cited hurricanes) and pest attacks (Ancona-Bates, 2017). More than half of the interviewees said that drought has a bigger impact during the growing and flowering stages of the maize cultivation cycle (August), while hurricanes have a greater impact when maize plants have ears (September). Interviewees also recognized that changes in rainy season patterns, such as a 1 or 2 month delay of the first rains (*maná ché*) or irregular rainfall, have strongly impacted milpa farming. These impacts translate to reduced yields, decreased milpa area, loss of diversity in crops/varieties, and concomitant food insecurity. They are also playing a role in the abandonment of: (a) cultivation practices such as dry sowing (*Tikin Muuk*); (b) weather prediction practices like the *Xook K'iin* (annual weather forecast); and (c) ceremonies such as the *Ch'a Cháak*. Interviewees also cited diseases associated with particular weather conditions like red clouds (*k'amk'ubul*), acid rains (*sabak ja'*), and hot water (*sacaba*), as well as associations between drought and attacks from pests such as wild birds (like parrots, woodpeckers, and quails) and mammals (badgers, raccoons, squirrels, mice, wild bores, and foxes).

The 2018 study on milpa sustainability enabled us to embed the importance of weather in the different functions that milpa systems play in producing food and other assets, contributing to the tropical ecosystem, and to reproducing culture (Briones-Guzmán and González-Esquivel, 2019). Study findings indicated that milpa sustainability contemplates these three functions. In the production of food and other asset for consumption and sale, milpa sustainability refers to the quantity, quality, and diversity of the harvest required to fulfill a family's food needs for a year and generate incomes that contribute to a decent life. For their contribution to the ecosystem, the sustainability of the milpa requires maintaining soil fertility, efficient management of the land, and not damaging nature with chemical pesticides. For reproducing Mayan culture, milpa sustainability refers to the participation of all family members in milpa activities and in the transmission of TEK to subsequent generations. The milpa contribution to conserving crop diversity and for facilitating the diversification of activities is also an important requirement for its sustainability. Diversity of crops/diets and diversified livelihoods have played an important role in responding to

TABLE 2 | Responses about the reliability and use of weather forecast methods from the 2018 study.

Weather forecast method	Reliable because it is a good reality proxy	More or less reliable because forecast has variable results	Not reliable because it is not a good reality proxy	Not used	Total
Xook K'iin	6 (11%)	14 (26%)	3 (6%)	31 (57%)	54 (100%)
Indicators from nature	12 (22%)	11 (20%)	2 (4%)	29 (54%)	54 (100%)
Indicators from sky	5 (9%)	4 (8%)	0 (0%)	45 (83%)	54 (100%)
External weather forecast	1 (2%)	21 (39%)	2 (4%)	30 (55%)	54 (100%)

Source: Database containing the information to measure indicators from the 2018 Study on Milpa Sustainability.

climate crises throughout the Maya history (Terán-Contreras and Rasmussen, 1995; Zizumbo-Villarreal et al., 2012) and are currently seen as key elements for combating climate change (FAO, 2013). From the semi-structure interviews made to 54 individual farmers we know that more than 50% of farmers use no weather forecasting methods (**Table 2**). Indicators from nature are regarded the most reliable (22%) while external weather forecasts (from television, radio, newspapers, or the internet) are deemed the least reliable (2%). Farmers do not consider external weather forecasts reliable because they are given at the regional or state level, vs. the local forecasts required for making decisions on planting and other cultivation practices. For the case of local weather methods (*Xook K'iin*[6] indicators from nature and indicators from sky), they consider that their reliability has been decreasing due to increased weather variability.

Although the general perception was that local weather forecast methods such as *Xook K'iin* and biological (from nature) and astronomic (from sky) indicators are not as reliable as before, participants expressed an interest in reviving them. For example, in one of focus groups participants proposed to work on agricultural calendars at the community level, using *Xook K'iin* as the base to model various planting scenarios depending on the diversity of varieties and crops and their adaptation and resistance to particular weather conditions. During these workshops participants also talked about common topics on climate change like risk distribution with phrases like "*for sustainability we need that we as peasants are able to recover after bad harvests and catastrophic events like hurricanes. For that we need not only the support of government but of society as a whole as now we are the ones who are dealing with all the risk*" (farmer from Yaxcaba, August 2018).

Traditional Knowledge for Weather Forecasting

TEK on weather covers various aspects from forecasting to adaptation to mitigation. We chose to focus on weather forecasting because study participants highlighted it as a particular interest. Weather prediction dates to the pre-Columbian times when Maya people used observations from the sky or their surroundings (*a paktik ka'an*), plants, insects, and animals to define agricultural cycles and mitigate negative weather effects on the milpa system. This knowledge persists with the *Xook K'iin* (annual weather prediction method) and with the complementary use of indicators from nature and the sky.

Xook K'iin

The Mayan *Xook K'iin*[7] is a longstanding method used to predict climate variations and phenomena (like hurricanes, droughts, and winds) throughout the year. It is based on detailed observations and accounts of sun intensity, cloud density, presence of fog, rain and low temperatures during each day of January. Some people give more importance to observations during the first 12 days of January, while others favor observations from January 12–24. Observations are normally made during daylight hours (from 6 a.m. to 6 p.m.) and, depending on the day of the month, they may cover all day, or specific hours during the day. Some people are meticulous making observation during the morning, afternoon, and evening as this indicates when during the month (initial days, middle days or and the last days) the phenomenon will take place. All these observations are registered to serve as predictors of each months' weather. A detailed description of this method can be found in Cat-Colli (2015) and Caamal-Itza (2017). *Xook K'iin* is commonly translated in Spanish as "*Cabañuelas*," as it is similar to the weather prediction methods practiced in Spain and the south of France (Fuentes Blanc and Fuentes Blanc, 2003). "Cabañuelas" resonates with Mayan ancestral weather forecasting methods like the ones based on the *Ha'ab* (Mayan solar calendar) used by pre-Columbian priests to define the agricultural cycle (Cat-Colli, 2015). Currently, a local organization named *Colectivo Xook K'iin* is promoting this and other traditional forecasting methods in the context of reinforcing Mayan identity and culture.

Mayan farmers use *Xook K'iin* to make decisions about the area that they are going to cultivate each year, the dates for burning (as part of land preparation) and sowing, the varieties and crops to be planted, the time for rituals, and the practices they will undertake to mitigate a bad rainy season or take advantage of a good rainy season. Farmers who use this method can only focus on major observations like identifying the start of the rainy season or develop a detailed yearly weather forecast to consider in

[6]*Xook K'iin* is a traditional forecast method used to predict climate variations and phenomena (like hurricanes, droughts, and winds) throughout the year. The next section describes it in more detail.

[7]This term is also written as *Xockin* (Granados Sánchez et al., 1999), *Xokk"iin* (Hernández Galindo, 2015), *Xok K'in* (Tuz-Chi, 2009), *Xokin* (Marquez-Míreles, 2006), and has two main meanings: the count of the days and the count of the days from the Sun.

their cultivation cycle. Interviewees who stated that they do not use *Xook K'iin* explained that they feel the method has become inaccurate due to changes in the rainy seasons (especially rain delays). **Figure 2** illustrates a *Xook Kiin* that we documented during fieldwork for the 2019 agricultural cycle. It shows that each month can have different forecast symbols concerning to weather events like a rainy, sunny and windy May (see **Figure 2**) meaning that this month will start with rains but in the middle will be sunny and at the end windy. As rains are important for germination it will be important to plant on the first week of May or first week of June when rains are expected. However, other considerations are important for defining the sowing date (as the rains during the flowering period).

Xook K'iin is complemented with other methods for weather forecasting, such as humidity predictions that predate the *Xook K'iin* and require 12 piles of salt divided in two lines of 6 piles to be placed on a table outside the house during the last night of the year (December 31st). Before the *Xook K'iin* count starts on January 1st, people check each pile and, if the pile disintegrates, there is going to be humidity that month of year.

Indicators From Nature and the Sky

There are long, worldwide traditions of weather forecasting based on the phenology of certain plants, the behavior of certain animals, and the patterns of the moon and sun. Indigenous groups from different parts of Mexico have developed TEK systems for weather prediction using these indicators (Albores and Broda, 1997; Miranda-Trejo et al., 2009; González-Pérez, 2013; Rivero-Romero et al., 2016). Our study gathered information on such indicators, as described in **Table 3**. These expression of bioculturality are used to predict the quality of the agricultural cycle (good or bad harvest) or the arrival of rain, drought, or hurricanes. Forecasts use different time scales from seasonal, medium-term (months), to short-term (2 or 3 days before the event happens). Few indicators are frequently used like the observation of *beek* flowering, ants behavior and *jabin* fruiting.

The interviewees stated that these methods are more reliable than external forecasts, but that they have been disrupted by climate change. As one interviewee said "*beforehand we were relying on nature but now with this crazy weather it seems that nature breaks its own laws. This because now we observe that trees are flowering in unusual times*" (informant from Peto, 2019). The role of plants and animals goes further than predictors. In the case of the Mayas of the Yucatán Peninsula, some of the animals used as predictors are sacred and are used in the representation of the *Ha'ab* (Mayan solar calendar). That is the case of toads, snakes, and sparrow hawks that are sacred because they announce the arrival of the rain (Valencia-Rivera, 2017). The same is for moon and sun, deities in the Mayan Cosmology and are used until now to define cultivation practices such as burning, planting and harvesting (Tuz-Chi, 2009).

The weather forecast analyzes and interprets both the *Xook K'iin* and indicators from nature and the sky to define daily,

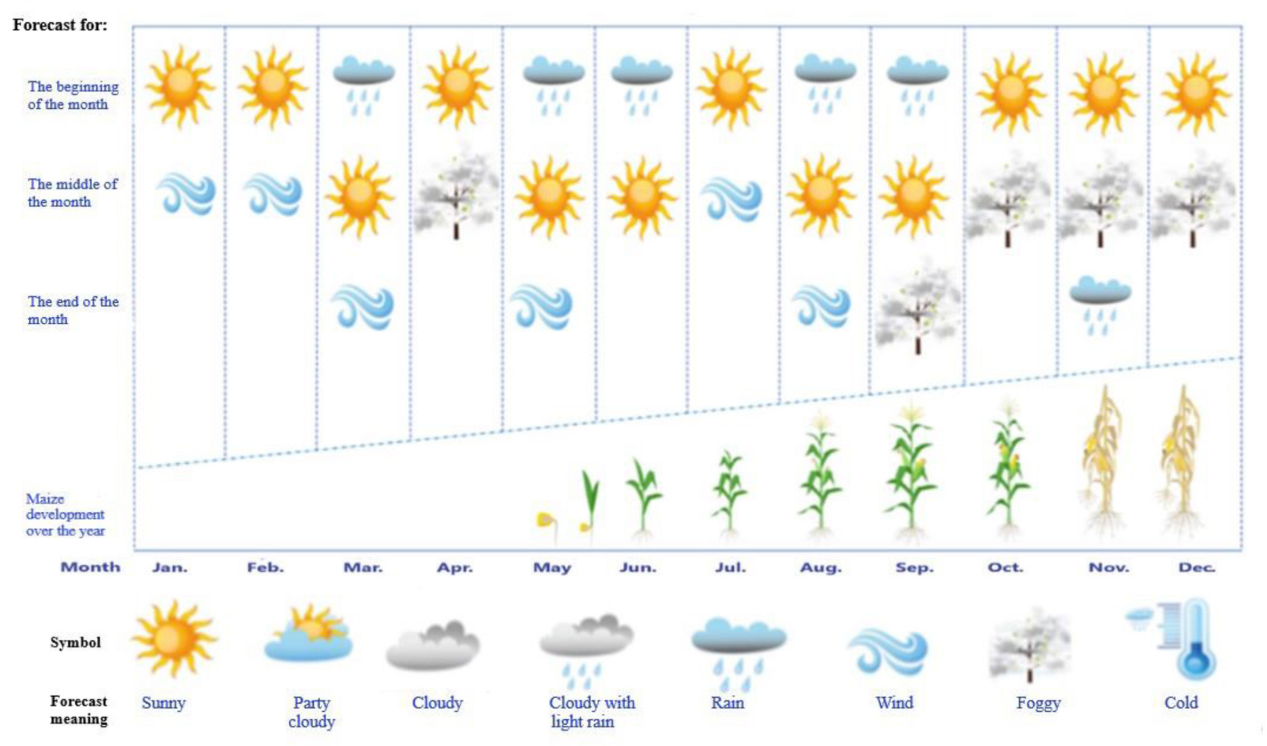

FIGURE 2 | *Xook K'iin* for the 2019 agricultural cycle in Yaxuna, Yaxcabá, Yucatán from the 2019 study.

TABLE 3 | Indicators from nature and the sky that are used to predict weather and agricultural cycles in the Yucatán Peninsula from the 2019 study.

Group	Names	Description	Prediction details
Plants	Local names: *Pich* (Maya), "parota" (Spanish), earpod trees (English) Scientific name: *Enterolobium cyclocarpum (Jacq.) Griseb*	The amount of fruit on earpod trees during March and April indicates whether there will be a good (trees with a lot of fruits) or bad (trees with few fruits) harvest.	Good or bad harvest Seasonal prediction Respondents: 3
	Local names: *Ya'ax che'* (Maya), "ceiba" (Spanish and English) Scientific name: *Ceiba pentandra* (L.) *Gaerth*	The amount of fruit on the ceiba trees during March and April indicates whether there will be a good (trees with a lot of fruits) or bad (trees with few fruits) harvest.	Good or bad harvest Seasonal prediction Respondents: 1
	Local names: *Beek* (Maya), "falso roble" (Spanish), Pinguica (English) Scientific name: *Ehretia tinifolia* L.	The flowering behavior of Pinguica indicates several factors. If it flowers in April and drops its flowers, there will be a bad harvest. Flowering in May indicates that a late planting will give a good harvest. In Quintana Roo, if the tree flowers is April and keeps its leaves, the milpa will have too many weeds but without leaves there will be few weeds.	Good or bad harvest Weeds abundance Seasonal prediction Respondents:11
	Local names: *Jahin* (Maya), "Jabin" (Spanish), Fish Fuddle (English) Scientific name: *Piscidia piscipula* L.	The amount of fruits and leaves during January and February indicates good (too much fruits and few leaves) or bad harvest (too much leaves and few fruits).	Good or bad harvest Seasonal prediction Respondents:7
Birds	Local names: *Baach* (Maya), "chachalaca" (Spanish and English) Scientific name: *Ortalis vetula*	*Chachalaca* song is used to predict imminent rain or drought. If the bird sings during the afternoon, it will take time to rain, but if it sings in the morning there will be rains in the next 2–3 days.	Rain and drought Short-term prediction Respondents:4
	Local names: *Yuya* (Maya), "calandria" (Spanish), Orange Oriole (English) Scientific name: *Icterus auratus*	The size and characteristics of Orange Oriole nests during April and May are also used to predict rain and drought. Long nests with green leaves predict a long drought as chicks will have more air. Long nests with dry leaves indicate that rainfall will arrive soon and planting can be prepared in April.	Rain and drought Seasonal prediction Respondents:3
	Local names: *Koos* (Maya), "guaco" (Spanish), Laughing falcon (English) Scientific name *Herpetotheres cachinnans*	The time of the laughing falcon song indicates rain and drought. If it sings in the morning, standing on a green branch, it will rain. However, if it sings in the afternoon on a dry branch, there will be drought or very few or delayed rains.	Rain and drought Seasonal forecast Respondents:3
	Local names: *Chak mucuy* (Maya), "tortola" (Spanish), Ruddy ground (English) Scientific name *Columbina talpacoti*	If ruddy ground doves build their nests in the soil, there will be droughts. If they establish their nests in a tree there are going to be rains.	Rain and drought Seasonal forecast Respondents:2
	Local names: *i'koos* (Maya), "gavilán" (Spanish), Sparrow hawk (English) Scientific name	The height at which the sparrow hawk sings predicts rain (near the soil) or a prolongated drought (high in the sky).	Rain and drought Seasonal forecast Respondents:4
Insects	Local names: *síinik* (Maya), "hormigas" (Spanish), ants (English) Scientific name: Formicidae	Rain indicators depend on ant behavior such as: (a) they leave the anthill and take their eggs to a more secure place; (b) protect their anthill digging around and putting soil in the entrance for avoiding floods; and (c) various species start flying. When army ants collect and store food there is going to be a drought.	Rain and drought Short-term forecast Respondents:11
	Local names: *k'uuruch* (Maya), "cucarachas" (Spanish), cockroaches (English) Scientific name: Blattodea	When cockroaches flutter around the houses it will rain within 3 days. It is assumed that these insects feel the heat and humidity.	Rain Short-term forecast Respondents: 1
	Local names: *x'mahaná* (Maya), "mariposa nocturna" (Spanish), Black with butterflies (English) Scientific name: *Ascalapha odorata*	When black witch butterflies enter the house during the day it will rain within 3 days. People think that it is asking for permission to stay safe at home and escape from rain.	Rain Short-term forecast Respondents:4
	Local names: *K'an ixím* (Maya), "escarabajo" (Spanish), beetles (English) Scientific name: Coleoptera	If during the nights of May there are too many beetles on the floor or flying around the lights, this is a sign of a good harvest.	Good or bad harvest Seasonal forecast Respondents:4
Amphibian	Local names: *muuch* (Maya), "sapos" (Spanish), toads (English) Scientific name: Bufonidae	When toads croak during the night they are indicating that rain will come within 3 days. If the "*carillo múuch*" toad croaks during April nights this predicts hurricanes.	Rain and hurricanes Short- and medium-term forecast Respondents:2
Reptile	Local names: *kan* (Maya), "serpiente" (Spanish), serpents (English) Scientific name: Serpentes	When serpents climb trees, they are expecting strong rains.	Rain Short-term forecast Respondents:1
	Local names: *huuh* (Maya), "iguana" (Spanish and English) Scientific name: Iguana	When iguanas make toad-like noises they are announcing rains. When they lay eggs and bury them during May and June, they are announcing the planting season	Rain Short- and medium-term forecast Respondents:1
Mammals	Local names: *ma'ax* (Maya), "monos" (Spanish), monkey (English) Scientific name: Primates	When monkeys howl during the night it will rain soon.	Rain Short-term forecast Respondents:1
Sky	Moon	When the Moon appears with a halo or when it is in the last quarter it is going to rain soon.	Rain Short-term forecast Respondents:2
	Sun	When the Sun has a crown of dominant blue color, it will rain soon. When the Sun has a crown and dominant red color, there will be drought.	Rain and drought Short-term forecast Respondents:3

Source: Data collected from the 2019 study on Traditional knowledge on weather.

monthly, and/or seasonal predictions. A key element to consider is the time of the day in which the phenomena take place, because they become proxies of the days during the month in which rain or drought will occur. The correlation between different type of methods increases the reliability of the prediction.

Mayan Cosmology on Rain and Weather

For Mayan people, weather forecasts are also highly tied to their cosmology or understanding of the world. The Mayan cosmology of rain and clouds includes a detailed description of how these phenomena occur explained by the presence of Mayan deities. Rain is vital for milpa farming, thus Mayan people continue to petition the gods and goddesses responsible for rain, through ceremonies such as *Ch'a Cháak*. Due to their importance for agriculture (Love, 2011; Russell, 2016), these deities have survived five centuries of colonization that imposed new (Christian) gods (Terán-Contreras and Rasmussen, 2008b). Here we describe the cosmology as expressed during the *Ch'a Cháak* praying documented during 2019 fieldwork and complemented by studies of Terán-Contreras and Rasmussen (2008a,b).

The *Ch'a Cháak* is led by God and the Virgin, divine representations of the new Christian order brought by the Spanish conquest, which have replaced the Sun (*Itzamná*) and the Moon (*Ixchel*) Gods from the Mayan creation of the world. Watering gods and goddesses are also present at the ceremony as they are the ones who make rain possible. All these gods have a place at the principal altar used in the ceremony. Other minor gods and supernatural beings related to the milpa farming are also invited to this ceremony. One such group is the *Metansayao'ob,* guardians of the cenotes, who decide if the watering gods can extract water from the cenotes for the rain. Another group are the owners of the animals known as *Metanlu'umo'ob,* who can prevent their animals from damaging the milpa. There are also the owners of the forest, *Yum kaxo'ob*^, who prevent accidents during the cultivation practices. Wind gods, *Iko'ob*, are also invited as they can make people sick. *Aluxo'ob* or *aluxes* are also invited to this ceremony because these supernatural beings take care of the milpa. Finally, the protectors of people (*santos uiniko'ob*) and the protectors of towns (*balamo'ob*) are also invited to this ceremony.

Ch'a Cháak lasts 3 days, including preparation, the ceremony, and cleaning. The gods take offertory and distribute it at a large party they have every year at last days of the *Ha'ab* (Mayan solar calendar) on July 16–20 in caves below the sea near the archaeological site of Tulum. The goddess *Cháak* acts as the notary; she registers when, where, and who gives the offertory and performs rituals and ceremonies for requesting good rains and harvests. This list is then used to define the rain distribution (Rasmussen, 1989). Rainfall will arrive if God forgives their sins[8] and allows the watering gods to perform their task in their milpas. Peasants who are not forgiven will not receive the "saint rain." God orders Saint Michael the Archangel (commander of the watering gods) together with the Virgin (the ward of the main source of water), to open the source of water for starting the rains[9]. According to their cosmology, the rain in the earth is the result of rain gods and goddess irrigating in the sky while they are riding their horses. Male gods go down to the cenotes, fill their *chujo'ob* or "*calabazos*" (natural containers made from *Lagenaria* plants) and return to the sky to disperse the water as rain. Mayan people do not believe that water comes from the sea because, if that was the case, the water would be salty, and distribution would be homogenous across milpa fields. For Mayan people, this explains rainfall variability and it is the basis for their relationship with gods and supernatural beings.

According to the cosmology, thunder and lighting is created when gods use their whips, whistles, and machetes. Goddesses disperse the water in drops avoiding the water showers with their cloaks (i.e., the clouds). There are 16 pairs of gods in groups of four that cover the four corners of the world: southeast, northeast, southwest, and northwest. One pair is the principal and the other three follow their orders. Each god and goddess have a name that is associated with the cardinal point from where he/she comes and with a color that identifies that point in the Mayan Cosmology[10]. Not all the pairs irrigate at the same time the same type of water as it depends of the cenote where they extract the water. Some people believe that these gods live in a palace in the sky, while, others believe that they dwell in the forest and make milpa using the water from the cenote at the archaeological site of Chichén Itzá. Each couple has its moment to water. If they start on time, rains will be plentiful but, if not, rains will cause damage. For example, during May to August when milpa is planted, rains from the southeast and east are the best. According to the cosmology, rains entering from another direction will damage the crops. In winter, the best rains come from the northwest and southwest; if the gods from the southeast enter with their rains, they will damage the crops. When the southeast gods are watering, the gods from west can work with them but only a little. Similarly, gods from the northeast can work with those from northwest without causing any harm.

Other gods of lower rank have names that allude to different aspects of clouds, such as the amount of rain they carry; if they are rainy or dry clouds; if they rain a lot of rain or a little; if it only forms mist, dew or gives shade; if it carries hail; or if it gives lightning, thunder, and wind but no rain. Mayan people also categorize clouds by how they transform themselves announce rain or drought (Hoil-Tzuc, 2020).

Previous studies reported that until the 1980's Mayan communities perceived hurricanes as the cosmic battle between the good and protective *Cháac* vs. the bad and destructive

[8]This idea of sin appears before Christianity, since de Landa (1959) reports the existence of sin and confession among the Mayans in the 16th century and it seems that it is one of the beliefs that favored, along with others, the entry of Christianity into Mesoamerica.

[9]Historical and ethnographic data indicate that Saint Michael the Archangel replaced Kukulkan, a god associated with fertility and rain, who was the former commander of the *Chaako'ob* (Terán-Contreras and Rasmussen, 2008b).

[10]For Maya Cosmology each cardinal point is associated to a color: The east and northeast are yellow; the north and northwest are black; the south and southeast are white; and west and southwest is red.

Cháac, but that currently this perception has changed (Campos-Goenaga, 2012). Angelotti-Pasteur (2014) found that Mayan people now believe that hurricanes can have natural or human causes not only a divine one, especially due to the discourse around climate change. In our study, while some interviewees attributed a divine explanation to hurricanes, others believe that they are completely uncontrolled as "*even God cannot control them*" (interviewee from Xocen) (Hoil-Tzuc, 2020). Similarly, people used to think that water that damages crops comes from special cenotes and is sent as a punishment from God via Saint Michael the Archangel (commander of the watering gods), but this viewpoint has mostly disappeared. Currently persons do not talk about cenotes with damaging water and think that Saint Michael is not obeying God (Hoil-Tzuc, 2020). This pattern is also shown with the *Ch'a Cháak* ceremony, which is now being performed less because Mayan people worldview has changed with the entrance of new religions and its reliability has decreased in the face of climate change.

Based on our findings, the understanding of different meteorological phenomena is based on the Mayan Cosmology and its intangible meanings. In that way the tangible elements and observations that conformed Mayan TEK on weather forecasting are entangled with their beliefs, values and ways to construct the world.

DISCUSSION

Weather forecasting knowledge of the Mayan people of the Yucatán Peninsula indicates an alternative pathway for integrating indigenous people and their knowledge into actions combating climate change in agriculture. Gregorio and Verschoor (2012) work with the Tikuna people in Colombia to show how they understand and deal with climate change. Similarly, Mayan people adapted to weather variation over millennia, and have developed strategies to cope with a changing environment. However, while Gregorio and Verschoor (2012) postulated that there is an ontological problem in matching indigenous communities' views on climate change with those of the western world, we believe that it is possible if we use an approach that voices indigenous people's understanding of climate change, i.e., that develops climate change action based not only on the material and physical description of the phenomena, but also on the cosmovision. We therefore propose a rights-based approach that considers food, work, territory, and indigenous rights (Tsosie, 2007; Borras Pentinat, 2013; Budiman, 2019). Our proposal also recognizes the rich body of local weather forecasting knowledge described in the previous section. Moving away from the dichotomic discourse of traditional vs. scientific knowledge, our proposal begins by recognizing that different types of knowledge are already being integrated. The use of external forecast information illustrates this and allows us to focus this discussion on the processes and contexts in which integration takes place in relation to indigenous groups claims on climatic justice. As these claims are captured on Fraser (2010) framework on scales of justice, we apply these scales to identify key issues that development actors—such as practitioners and scientists—should account for in integrating indigenous communities and their TEK in actions to combat climate change.

Equality in Redistribution

Indigenous claims on distributional justice are associated with two key elements that should be considered in climate change interventions. The first element covers the claims on the context of the inequality experienced by indigenous people. From a social justice perspective, interventions combating climate change should account for the context of historical and structural inequalities that have been experienced and should commit to reducing poverty and marginalization (Doolittle, 2010). This engagement is justified first because it serves to accomplish basic human rights that are pending issues for indigenous communities (Davies et al., 2009; ILO, 2017), and because it refers to the conception of vulnerability in social systems involving unequal power relations (Chandra et al., 2017). Both aspects can be observed in the regional history of the Yucatán Peninsula, where the impacts of climatic hazards (e.g., drought) were magnified by social phenomena. This social context defines the institutional support required for the sustainability and resilience of sociobiological systems like the milpa (Terán-Contreras and Rasmussen, 1995; Fisher, 2020) and its capacity to reduce the impacts of climate change by reallocating resources that decrease existing social inequalities (Schlosberg and Collins, 2014).

The second element to consider in distributional justice examines the process in which different types of knowledge interact and receive benefits from interventions combating climate change. The wealth of weather forecasting methods used not only by indigenous Mayan farmers in the Yucatán Peninsula but also by other indigenous groups worldwide (Galacgac and Balisacan, 2001; Acharya, 2011; Garay-Barayazarra and Puri, 2011; Jiri et al., 2016) raises the question of why they have received limited support for climate change action. Moreover, indigenous farmers have incorporated external forecasts from scientific sources into their decision-making processes, which shows how they are actively integrating different types of knowledge. Therefore, we propose that resources (not only economic but also financial and human resources) from climate change actions be assigned to local efforts of weather forecasting, such as the *Colectivo Xook K'iin* for promoting processes of knowledge actualization (Nonaka, 1994), and that these efforts are supported by external weather forecast experts. In other words, taking TEK as the departure point and building on it, rather than beginning with scientific knowledge and trying to fit it to indigenous communities. Changing our approach as development practitioners will affect power relations concerning who has access and control over resources labeled for combating climate change and will make it more just for indigenous peoples.

Justice in Recognition

Indigenous claims on the recognition scale of justice refer to their cultural rights. The fact that Mayan TEK on weather forecasting can be traced to the pre-Columbian Mayan civilization demonstrates that this knowledge is important not only for agricultural production but also for reproducing Mayan culture. Reproducing this culture after five centuries of interactions with a western culture that brought colonization, modernization, and globalization has meant using European forecast methods like the "*Cabañuelas*" for continuing with their ancestral method based on the *Ha'ab* (Mayan solar calendar) in the current *Xook K'iin*. It has also meant integrating Catholic deities to rituals like the *Ch'a Cháak*. As both the *Xook K'iin* and *Ch'a Cháak* are part of milpa farming, this traditional farming system has become a haven for pre-Columbian cosmovision and religious practice, as many temples were destroyed during the conquest and Colonial era (Florescano, 2000). Milpa plays a key role in maintaining Maya culture because its agricultural calendar is also a religious calendar that combines astronomic and meteorological phenomena with farming practices, rituals, and ceremonies (Florescano, 2000). In that sense, Mayan TEK on weather forecasting becomes an expression of cultural resistance with methods and practices such as *Xook K'iin* and *Ch'a Cháak* and their potential losses will represent what Tsosie (2007) calls cultural harm.

Agricultural development interventions have not necessarily been sensitive to the cultural dimension of farming and have resulted in traditional knowledge loss, changes in cultural norms, disruption to local forms of organization and communication and to intergenerational transmission of identity and culture (Grenier, 1999; Agrawal, 2002; Mafongoya and Ajayi, 2017). Cultures are not fixed or immutable and can be intentionally or unintentionally affected by interventions (Mukhopadhyay, 1995), thus development actors should reflect on how they support specific worldviews over others as part of the ontological and epistemological differences between theirs and indigenous worldviews (Briggs and Sharp, 2004). Here, reflection implies deconstructing deep development assumptions on knowledge and power for embracing the cosmological dimension of TEK. Practitioners' reflections should then prevent them from causing cultural harm by consciously or unconsciously blocking or precluding indigenous people's access to their own cosmovision and cultural systems (Tsosie, 2007). Ceremonies such as *Ch'a Cháak* should be recognized as key activities within milpa farming as planting and harvesting and should receive support from development actors. There is therefore an urgent need for development actors to deconstruct development and science assumptions and facilitate the transition to a pluriverse approach that embraces epistemological diversity (Escobar, 2018).

Equality in Representation

The last scale of justice complements the previous ones by considering the processes of decision-making in climate change interventions. This is particularly important in recognizing and supporting the *Ch'a Cháak* ceremony, the *Xook K'iin*, and indicators of nature and the sky, and explains the importance of indigenous movements' claims on self-determination in decision-making processes that affect them (Schlosberg and Collins, 2014; Ludwig and Macnaghten, 2019). This scale of justice was advanced with the Indigenous peoples' right to "Free, Prior, and Informed Consent (FPIC)" outlined in the 2007 UN Declaration on the Rights of Indigenous Peoples (Raftopoulos and Short, 2019). This concept contemplates the rights of participation, consultation, and self-determination as a way to recognize the historic injustices that they have suffered (McGee, 2009). The Cancun Agreement of 2010 adopted seven non-mandatory safeguards for REDD+ projects in which the full and effective participation of relevant stakeholders (in particular indigenous peoples and local communities) was integrated. As both the FPIC concept and the social safeguards scheme represent an important advancement in this scale of justice, we propose that they should also be considered in interventions combating climate change in agriculture. They can serve as frameworks to improve transparency in governance processes and ensure the participation and decision-making power of indigenous people in these processes.

Countries have advanced the implementation of the FPIC concept and social safeguards in the context of REDD+. For example, Mexico developed a protocol to implement FPIC that is currently in process to become law (Adriano-Anaya, 2018). For social safeguards, Mexico has been working on this concept in the context of implementing REDD+ projects (Deschamps and Zúñiga, 2015) that illustrates challenges for achieving the full participation and contribution to decision-making of not only indigenous people but local communities in general. Challenges appeared in changing the top-down practices of development actors like governments or NGOs that perpetuate unequal power relations between implementers and local communities (Almanza Alcalde et al., 2020). Challenges also appeared around the relationship between knowledge and power expressed by the dominant scientific narratives that explain the problem of climate change and define its solutions with a complex language that does not facilitate conversations with local partners (Fadnes, 2014). Power dynamics at the local level, in which influential and wealthy persons participate and marginalized stakeholders like women, indigenous communities, and youth are excluded, also represent challenges that are not easy to overcome (Garduño-Díaz, 2012). As it is not easy to tackle historical practices of clientelism and paternalism that have weakened organizational processes and hindered the identification of legitimate interlocutors that represent local communities (Trench et al., 2018). In the center of the discussion is the matter of power relations and dynamics between and within different stakeholders for ensuring transparent and equitable decision-making processes. Accounting for all these challenges is key for advancing in procedural justice.

Our proposal for integrating indigenous people and their TEK in agricultural actions combating climate change implies a social justice perspective grounded in a rights-based approach. This perspective asks development actors to analyze power dynamics and relations recreated by different stakeholders during interventions and that promote particular worldviews over others by facilitating resources and by creating spaces of participation in decision-making processes. Moreover, it asks them to challenge their own assumptions on knowledge and development and to reflect on their own position in these interventions. At the core of the reflection, development actors should ask themselves the questions of who contributes to whom in coping with climate change?

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by CIMMYT Institutional Ethics in Research Committee (IREC.2020.024). Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

T-CV has coordinated the writing process and led the Introduction, Historical Importance, and Discussion sections. T-MC has provided input and has contributed to the writing of all the sections. A-RL has contributed to the writing of the Information Sources and Analysis section as well as collecting, analyzing, and writing part of the Results section. MH-T has collected, analyzed data, and participated in the writing of the Results section. ST-C has written part of the Results section and has provided input for all the other sections. All authors contributed to the article and approved the submitted version.

FUNDING

Data collection took place in the context of the project Modernización Sustentable de la Milpa en la Península de Yucatán implemented by the International Maize and Wheat Centre (CIMMYT) with the sponsorship of Fundación Haciendas del Mundo Maya, A. C. and Fomento Social Banamex. Manuscript writing was possible with the support of the project Modernización de la Agricultura Tradicional (MasAgro) implemented by CIMMYT and sponsorship by the Secretaria de Agricultura y Desarrollo Rural (Secretariat of Agriculture and Rural Development) of the Mexican Government. The publication was further supported by the CGIAR Research Program on maize agri-food systems (CRP MAIZE). The contents and opinions expressed herein are those of the authors and do not necessarily reflect the views of the associated and/or supporting institutions.

REFERENCES

Acharya, S. (2011). Presage biology: lessons from nature in weather forecasting. *Indian J. Tradit. Knowl.* 10, 114–124.

Adriano-Anaya, J. (2018). La judicialización del derecho a la consulta de los pueblos indígenas y el consentimiento libre, previo e informado. *Perfiles de Las Ciencias Soc.* 6, 194–216.

Agrawal, A. (1995). Dismantling the divide between indigenous and scientific knowledge. *Dev. Change* 26, 413–439. doi: 10.1111/j.1467-7660.1995.tb00560.x

Agrawal, A. (2002). Introducción: a favor de la indeterminación. *Rev. Int. Ciencias Soc.* 173, 121–130.

Alayón-Gamboa, J. A., and Ku-Vera, J. C. (2011). Vulnerability of smallholder agriculture in Calakmul, Campeche, Mexico. *Indian J. Tradit. Knowl.* 10, 125–132.

Albores, B., and Broda, J. (1997). *Graniceros: cosmovisión y meteorología indígenas de Mesoamérica*. El Colegio Mexiquenses A.C. y el Instituto de Investigaciones Históricas UNAM. Ciudad de Mexico, 563.

Almanza Alcalde, H., Satyal, P., Soto Sánchez, A. P., and Pskowski, M. (2020). REDD+ en México: Conflictividad en la implementación temprana de REDD+ en México. *Sociedad y Ambiente* 22, 152–179. doi: 10.31840/sya.vi22.2092

Ancona-Bates, P. (2017). *Línea base del sistema milpa Hub Península de Yucatán: Proyecto "Modernización de la Milpa Sustentable", Etapa 1 en 6 Municipios*. Texcoco: Internal report International Maize and Wheat Improvement Center, 80.

Angelotti-Pasteur, H. G. (2014). Percepción, miedo y riesgo, ante los huracanes y otros fenómenos naturales en Yucatán. *Temas Antropol. Rev. Investig. Regionales* 36, 43–72.

Barrera-Rojas, M. A., and Reyes-Maya, O. (2013). Pobreza y transferencias monetarias en comunidades mayas de México : José María Morelos y Sabán, Quintana Roo, 2011. *Rev. Econ. Política Soc.* 9, 201–228.

Borras Pentinat, S. (2013). "La justicia climática: entre la tutela y la fiscalización de las responsabilidades climate justice: between the guardianship and the fiscalization of responsibilities," in *Anuario Mexicano de Derecho Internacional*. Vol. 13. Available online at: http://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S1870-46542013000100001

Borras Pentinat, S. (2016). Movimientos para la justicia climática global: replanteando el escenario internacional del cambio climático. *Relaciones Int.* 33, 97–119. doi: 10.22201/iij.24487872e.2013.13.426

Bracamontes-Sosa, P. (2009). Sistema de pensamiento maya y pobreza socioeconómica. *Península* 4, 103–133.

Briggs, J., and Sharp, J. (2004). Indigenous knowledges and development: a postcolonial caution. Third *World Q.* 25, 661–676. doi: 10.1080/01436590410001678915

Briones-Guzmán, C., and González-Esquivel, C. E. (2019). *Reporte Técnico: evaluaciones de sustentabilidad (MESMIS) en cuatro estudios de caso en la Península de Yucatán*. Internal report Grupo Interdisciplinario de Tecnologia Rural Apropiada A.C. Morelia, 33.

Budiman, I. (2019). Climate-smart agriculture policy and (in)justice for smallholders in developing countries. *Future Food J. Food Agricul. Soc.* 7, 31–41. doi: 10.4018/978-1-7998-0125-2.ch002

Caamal-Itza, B. (2017). *Xok k'iin 2017: Cabañuelas Mayas.* Merida: Colectivo Xok K'íin, 10.

Cabañas, R. T. (2014). Historia de la climatología astronómica. Del neolítico a la época de Ptolomeo. *Rev. Climatol.* 14, 71–80.

Cameron, E. S. (2012). Securing indigenous politics: a critique of the vulnerability and adaptation approach to the human dimensions of climate change in the canadian arctic. *Global Environ. Change* 22, 103–114. doi: 10.1016/j.gloenvcha.2011.11.004

Campos-Goenaga, M. I. (2012). Sobre tempestades con remolino y plagas de langosta. Siglos XVI al XVIII en la península de Yucatán. *Relaciones. Estudios de Historia y Sociedad*, XXXIII, 125–160.

Cat-Colli, M. Á. (2015). *Xooc K'íin: Las Cabañuelas Mayas*. Universidad de Quintana Roo. Available online at: http://risisbi.uqroo.mx/handle/20.500.12249/1067

Chandra, A., McNamara, K. E., and Dargusch, P. (2017). The relevance of political ecology perspectives for smallholder climate-smart agriculture: a review. *J. Political Ecol.* 24, 821–842. doi: 10.2458/v24i1.20969

CONEVAL (2015). *Informe de pobreza en los municipios de México 2015, Vol.* 53. Ciudad de Mexico: CONEVAL.

Dahlin, B. H., Beach, T., Luzzadder-Beach, S., Hixson, D., Hutson, S., Magnoni, A., et al. (2005). Reconstructing agricultural self-sufficiency at Chunchucmil, Yucatan, Mexico. *Ancient Mesoamerica* 16, 229–247. doi: 10.1017/S0956536105050212

Dao, L. U. (2011). *The Role of Rain in Post Classic Maya Religious Belief.* University of Central Florida.

Davies, M., Guenther, B., Leavy, J., Mitchell, T., and Tanner, T. (2009). Climate change adaptation, disaster risk reduction and social protection:

complementary roles in agriculture and rural growth? *IDS Work. Papers* 2009, 01–37. doi: 10.1111/j.2040-0209.2009.00320_2.x

de Landa, D. (1959). *Relacion de las cosas de Yucatan*. Mexico: Editorial Porrua.

Deschamps, P., and Zúñiga, I. (2015). *Salvaguardas REDD + en México*. Mexico: Consejo Mexicano Para La Silvicultura Sostenible, 44.

Doolittle, A. A. (2010). The politics of indigeneity: Indigenous strategies for inclusion in climate change negotiations. *Conserv. Soc.* 8, 286–291. doi: 10.4103/0972-4923.78142

Douglas, P. M. J., Demarest, A. A., Brenner, M., and Canuto, M. A. (2016). Impacts of climate change on the collapse of lowland maya civilization. *Annu. Rev. Earth Planet. Sci.* 44, 613–645. doi: 10.1146/annurev-earth-060115-012512

Ebel, R., Méndez Aguilar, M., de, J., and Putnam, H. (2018). Milpa: one sister got climate-sick. The impact of climate change on traditional Maya farming systems. *Int. J. Sociol. Agricul. Food* 24, 175–199. doi: 10.48416/ijsaf.v24i2.103

Ebert, C. E., Hoggarth, J. A., Awe, J. J., Culleton, B. J., and Kennett, D. J. (2019). The role of diet in resilience and vulnerability to climate change among early agricultural communities in the maya lowlands. *Curr. Anthropol.* 60, 589–601. doi: 10.1086/704530

Eriksen, S. H., Cramer, L. K., Vetrhus, I., and Thornton, P. (2019). Can climate interventions open up space for transformation? Examining the case of climate-smart agriculture (CSA) in Uganda. *Front. Sustain. Food Syst.* 3, 1–17. doi: 10.3389/fsufs.2019.00111

Escobar, A. (2018). *Designs for the Pluriverse: Radical Interdependence, Autonomy, and the Making of Worlds. In New Ecologies for the Twenty-First Century*. (Durham; London: Duke University Press).

Estrada-Medina, H., Cobos-Gasca, V., Acosta-Rodríguez, J. L., Fierro, S. P., Castilla-Martínez, M., Castillo-Carrillo, C., et al. (2016). La sequía de la península de Yucatán. *Tecnol. Ciencias Del Agua* 7, 151–165.

Fadnes, I. (2014). *La despolitización de la ecología: Un análisis del proceso REDD+: México y Chiapas*. Universitas Osloensis.

FAO (2013). *Climate-Smart Agriculture: Sourcebook*. Rome: Food and Agriculture Organization of the United Nations, 570.

FAO-SAGARPA (2014). *México: el sector agropecuario ante el desafío del cambio climático*. Ciudad de Mexico: Organizacion de las Naciones Unidas para la Alimentacion and Secretaria de Agricultura, Ganaderia y Desarrollo Rural, Pesca y Alimentacion, 437.

Faust, B. B. (2001). Maya environmental successes and failures in the Yucatan Peninsula. *Environ. Sci. Policy* 4, 153–169. doi: 10.1016/S1462-9011(01)00026-0

Fedick, S., Allen, M., and Gomez-Pompa, A. (2003). *The Lowland Maya Area: Three Millennia at the Human-Wildland Interface*. New York, NY: Food Products Press.

Fisher, C. (2020). Maize politics and Maya farmers' traditional ecological knowledge in Yucatán, 1450–1600. *Hum. Ecol.* 48, 33–45. doi: 10.1007/s10745-020-00134-8

Florescano, E. (2000). La visión del cosmos de los indígenas actuales. *Desacatos* 5, 15–29. doi: 10.29340/5.1219

Frappier, A. B., Pyburn, J., Pinkey-Drobnis, A. D., Wang, X., Corbett, D. R., and Dahlin, B. H. (2014). Two millennia of tropical cyclone-induced mud layers in a northern Yucatán stalagmite: multiple overlapping climatic hazards during the Maya Terminal Classic "megadroughts." *Geophys. Res. Lett.* 41, 5148–5157. doi: 10.1002/2014GL059882

Fraser, N. (2010). *Scales of Justice: Reimagining Political Space in a Globalizing World*. New York, NY: Columbia University Press, 236.

Frischmann, D. (2001). La construcción del sujeto poscolonial en el discurso escénico maya contemporáneo de México. *Tramoya* 68, 102–116.

Fuentes Blanc, J., and Fuentes Blanc, A. (2003). Las cabañuelas o la predicción del tiempo en el saber popular. *Nimbus* 11–12, 151–157.

Galacgac, E. S., and Balisacan, C. M. (2001). Traditional weather forecasting methods in Ilocos Norte. *Philipp. J. Crop. Sci.* 26, 5–14.

Garay-Barayazarra, G., and Puri, R. K. (2011). Smelling the monsoon: Senses and traditional weather forecasting knowledge among the Kenyah Badeng farmers of Sarawak, Malaysia. *Indian J. Tradit. Knowl.* 10, 21–30.

Garduño-Díaz, P. Y. (2012). *Social safeguards for REDD + in Mexico ' s Watershed Management Program*. Uppsala University.

Gobierno de Quintana Roo (2013). *Programa Estatal de Acción ante el Cambio Climático* Estado de Quintana Roo: Universidad de Quintana Roo, 116.

Gobierno del Estado Yucatan (2014a). *Análisis de la vulnerabilidad actual y futura ante los efectos del cambio climático*. Merida: Factor CO_2, Cinvestav-IPN, EPOMEX, Secretaria de Desarrollo Urbano y Medio Ambiente del Gobierno del Estado de Yucatan, Instituto Nacional de Ecologia y Cambio Climatico y Banco Interamericano de Desarrollo, 172.

Gobierno del Estado Yucatan (2014b). *Programa Especial de Acción ante el Cambio Climático del Estado de Yucatán*. Merida: Diario Oficial del Gobierno del Estado de Yucatan. No. 32,568. Sabado 26 de Abril de 2014, 120.

González-Pérez, D. (2013). *Anuncios de tempestad: Predicciones del temporal en la etnoclimatología de los zapotecos del sur de Oaxaca, México*. IX Congreso Centroamericano de Antropologia, Territorio, Recursos Naturales y Sociedades Locales, 1–26.

Granados Sánchez, D., Florencia, G., Ríos, L., and Murcia, E. T. (1999). La milpa en la zona maya de Quintana Roo. *Rev. Geogr. Agric.* 28, 57–72.

Gregorio, J., and Verschoor, G. (2012). *"Climate Change Victims" or "World repairmen"?: A Socio-Ecological Innovation for Sustainability in the Colombian Amazon. Course Material in Communities, Conservation and Development*. Wageningen, NL: Wageningen Univeristy.

Grenier, L. (1999). *Conocimiento Indígena Guía para el investigador Contenido*. Available online at: https://www.portalces.org/sites/default/files/migrated/docs/1225.pdf

Haraway, D. (1988). Situated knowledges: the science question in feminism and the privilege of partial perspective. *Feminist Stud.* 14, 575–599. doi: 10.2307/3178066

Hernández Galindo, F. (2015). *Sistematización de la experiencia de la Escuela de Agricultura Ecológica U Yits Ka'an y su efecto sobre los medios de vida de las familias participantes en el municipio de Maní, Yucatán, México*. Centro Agronómico Tropical de Investigación y Enseñanza, Turrialba, 75.

Hiwasaki, L., Luna, E., Syamsidik, and Shaw, R. (2014). Process for integrating local and indigenous knowledge with science for hydro-meteorological disaster risk reduction and climate change adaptation in coastal and small island communities. *Int. J. Disaster Risk Reduc.* 10, 15–27. doi: 10.1016/j.ijdrr.2014.07.007

Hoggarth, J. A., Restall, M., Wood, J. W., and Kennett, D. J. (2017). Drought and its demographic effects in the maya lowlands. *Curr. Anthropol.* 58, 82–113. doi: 10.1086/690046

Hoil-Tzuc, M. (2020). *Taxonomía de nubes mayas en el Oriente de Yucatán*. Merida: Internal report International Maize and Wheat Improvement Center (CIMMYT), 12.

ILO (2017). *Indigenous Peoples and Climate Change: From Victims to Change Agents Through Decent Work (Gender, Equality and Diversity Branch. Green Jobs Programme)*. Geneva: International Labour Office, 56.

INEGI (2005). *Perfil Sociodemográfico de la Población Hablante de Maya*. http://internet.contenidos.inegi.org.mx/contenidos/productos/prod_serv/contenidos/espanol/bvinegi/productos/historicos/76/702825498191/702825498191_5.pdf

INEGI (2015). *Encuesta intercensal 2015*. Instituto Nacional de Estadística y Geografía.

Islebe, G. A., Torrescano-Valle, N., Aragón-Moreno, A. A., Vela-Peláez, A. A., and Valdez-Hernández, M. (2018). The Paleoanthropocene of the Yucatán Peninsula: Palynological evidence of environmental change. *Boletin de La Soc. Geol. Mexic.* 70, 49–60. doi: 10.18268/BSGM2018 v70n1a3

Jiri, O., Mafongoya, P. L., Mubaya, C., and Mafongoya, O. (2016). Seasonal climate prediction and adaptation using indigenous knowledge systems in agriculture systems in Southern Africa: a review. *J. Agricul. Sci.* 8, 156–172. doi: 10.5539/jas.v8n5p156

Joseph, G. M. (1985). From caste war to class war: the historiography of modern Yucatán (c. 1750-1940). *Hispanic Am. Hist. Rev.* 65, 111–134. doi: 10.1215/00182168-65.1.111

Karlsson, L., Nightingale, A., Thompson, J., and Naess, L. O. (2017). ""Triple wins" or "triple faults"?Analysing policy on climate-smart agriculture," in *CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Working paper No. 197*, 43.

Konrad, H. W. (2003). Caribbean tropical storms: ecological implications for pre-hispanic and contemporary Maya subsistence on the Yucatan Peninsula. *Rev. Univ. Autón. Yucatán* 224, 99–126.

Lemos, M. C., and Dilling, L. (2007). Equity in forecasting climate: can science save the world's poor? *Sci. Public Policy* 34, 109–116. doi: 10.3152/030234207X190964

Lipper, L., Thornton, P., Campbell, B. M., Baedeker, T., Braimoh, A., Bwalya, M., et al. (2014). Climate-smart agriculture for food security. *Nat. Clim. Change* 4, 1068–1072. doi: 10.1038/nclimate2437

López-Ridaura, S., Masera, O., and Astier, M. (2000). Evaluating the sustainability of integrated peasantry systems - the MESMIS Framework. *Ecol. Indicat.* 35, 1–14. doi: 10.1016/S1470-160X(02)00043-2

Love, B. (2011). The gods of Yucatán from A.D. 1560 to 1980. *Estudios de Cultura Maya* 37, 121–148. doi: 10.19130/iifl.ecm.2011.37.16

Ludwig, D., and Macnaghten, P. (2019). Traditional ecological knowledge in innovation governance: a framework for responsible and just innovation. *J. Respons. Innovat.* 7, 26–44. doi: 10.1080/23299460.2019.1676686

Macchi, M., Oviedo, G., Gotheil, S., Cross, K., Boedhihartono, A., Wolfangel, C., et al. (2008). "Indigenous and traditional peoples and climate change issues paper," in *Diversity*. https://www2.ohchr.org/english/issues/climatechange/docs/IUCN.pdf

Mafongoya, P. L., and Ajayi, O. C. (2017). *Indigenous Knowledge Systems and Climate Change Management in Africa*. Wageningen: CTA, 316.

Makridakis, S. (1986). The art and science of forecasting: an assessment and future directions. *Int. J. Forecast.* 2, 15–39. doi: 10.1016/0169-2070(86)90028-2

Mardero, S., Schmook, B., Christman, Z., Nickl, E., Schneider, L., Rogan, J., et al. (2014). "Precipitation variability and adaptation strategies in the Southern Yucatán Peninsula, Mexico: integrating local knowledge with quantitative analysis," in *International Perspectives on Climate Change*, eds W. Leal Filho, F. Alves, S. Caiero, and U. M. Azeiteiro (New York, NY: Springer Science & Business Media), 189–201.

Mardero, S., Schmook, B., Radel, C., Christman, Z., Lawrence, D., Millones, M., et al. (2015). Smallholders adaptations to droughts and climatic variability in southeastern Mexico. *Environ. Hazards* 14, 271–288. doi: 10.1080/17477891.2015.1058741

Mariaca Méndez, R. (2015). La Milpa Maya Yucateca en el Siglo XVI: evidencias Etnohistóricas y Conjeturas. *Etnobiología* 13, 1–25.

Marquez-Míreles, L. E. (2006). El agua, los huracanes y los rituales agrícolas en El Naranjal, Quintana Roo. *Perspect. Latinoam.* 3, 114–126.

Martín-Castillo, M. (2016). Milpa y capitalismo: opciones para los campesinos Mayas Yucatecos contemporáneos. *Revista LiminaR. Estudios Sociales y Humanísticos* 14, 101–114. doi: 10.29043/liminar.v14i2.463

McGee, B. (2009). The community referendum: participatory democracy and the right to free, prior and informed consent to development. *Berkeley J. Int. Law* 27, 570–635. doi: 10.15779/Z38T94C

Metcalfe, S. E., Schmook, B., Boyd, D. S., De la Barreda-Bautista, B., Endfield, G. E., Mardero, S., et al. (2020). Community perception, adaptation and resilience to extreme weather in the Yucatan Peninsula, Mexico. *Reg. Environ. Change* 20, 1–15. doi: 10.1007/s10113-020-01586-w

Milbrath, S. (2016). Evidencias de agroastronomía entre los antiguos Mayas. *Estudios de Cultura Maya* 47, 11–29. doi: 10.19130/iifl.ecm.2016.47.738

Miranda-Trejo, J., Herrera-Cabrera, B.., Paredes-Sanchez, J. A., and Delgado-Alvarado, A. (2009). Conocimiento tradicional sobre predictores climaticos en la agricultura de los Llanos de Serdan, Puebla, Mexico. *Trop. Subtrop. Agroecosyst.* 10, 151–160.

Molden, D. (2013). Water for food water for life: a comprehensive assessment of water management in agriculture. Earthscan, London: Internatinal Water Management Institute, 48.

Morales-Damián, M. (2017). Dioses sembradores en el Códice Madrid. *Rev. Xihmai* XII, 27–48.

Mukhopadhyay, M. (1995). Gender relations, development practice and 'culture.' *Gender Dev.* 3, 13–18. doi: 10.1080/741921766

Murphy, A. H. (1993). What is a good forecast? An essay on the nature of goodness in weather forecasting. *Weather Forecast.* 8, 281–293. doi: 10.1175/1520-0434(1993)008<0281:WIAGFA>2.0.CO;2

Nair, P. K. R., Viswanath, S., and Lubina, P. A. (2017). Cinderella agroforestry systems. *Agrofor. Syst.* 91, 901–917. doi: 10.1007/s10457-016-9966-3

Nakashima, D. J., GallowayMclean, K., Thulstrup, H. D., Ramos Castillo, A., and Rubis, J. T. (2012). *Weathering Uncertainty: Traditional Knowledge for Climate Change Assessment and Adaptation*. Paris: UNESCO and Darwin, UNU, 120.

Newell, P., and Taylor, O. (2018). Contested landscapes: the global political economy of climate-smart agriculture. *J. Peasant Stud.* 45, 108–129. doi: 10.1080/03066150.2017.1324426

Nonaka, I. (1994). A dynamic theory of organizational knowledge creation. *Org. Sci.* 5, 14. doi: 10.1287/orsc.5.1.14

Orlove, B. S., Chiang, J. C. H., and Cane, M. A. (2002). Ethnoclimatology in the Andes: a cross-disciplinary study uncovers a scientific basis for the scheme Andean potato farmers traditionally use to predict the coming rains. *Am. Sci.* 90, 428–435. doi: 10.1511/2002.33.791

Paoli Bolio, F. J. (2017). *La Guerra de Castas en Yucatán*. Merida: Editorial Dante.

Pat-Fernández, J., López-López, R., van der Wal, H., and Villanueva-Gutierrez, R. (2012). Organización social productiva: situación y perspectiva apícola de la sociedad unapincare en la Reserva de la Biosfera Los Petenes, Campeche, México. *Reg. Soc.* 24, 201–230. doi: 10.22198/rys.2012.54.a153

Quinta, E. F., Bastarrachea, J. R., Briceño, F., Medina, M., Petrich, R., Rejón, L., et al. (2003). "Solares, rumbos y pueblos: organización social de mayas peninsulares," in *La comunidad sin limites. La estructura social y comunitaria de los pueblos indígenas de México (Primera ed)*, eds S. Millan and J. Valle (Mexico: CONACULTA-INAH).

Raftopoulos, M., and Short, D. (2019). Implementing free prior and informed consent: the United Nations Declaration on the Rights of Indigenous Peoples (2007), the challenges of REDD+ and the case for the precautionary principle. *Int. J. Hum. Rights* 23, 87–103. doi: 10.1080/13642987.2019.1579990

Rasmussen, C. H. (1989). El Año Nuevo prehispánico: una costumbre viva, el help o cambio de chako'ob en Xocen. *Rev. Univ. Autón. Yucatán* 171, 14–16.

Reed, N. A. (2001). *The Caste War of Yucatán (Revised Ed)*. Stanford, CA: Stanford University Press.

Rivero-Romero, A. D., Moreno-Calles, A. I., Casas, A., Castillo, A., and Camou-Guerrero, A. (2016). Traditional climate knowledge: a case study in a peasant community of Tlaxcala, Mexico. *J. Ethnobiol. Ethnomed.* 12, 1–11. doi: 10.1186/s13002-016-0105-z

Rodríguez-Robayo, K. J., Méndez-López, M. E., Molina-Villegas, A., and Juárez, L. (2020). What do we talk about when we talk about milpa? A conceptual approach to the significance, topics of research and impact of the mayan milpa system. *J. Rural Stud.* 77, 47–54. doi: 10.1016/j.jrurstud.2020.04.029

Romero Conde, P. (1994). *La milpa y el origen del calendario maya*. Merida: Universidad Autónoma de Yucatán.

Russell, B. W. (2016). All the Gods of the World: Modern Maya Ritual in Yucatán, Mexico. *Ethnoarchaeology* 8, 4–29. doi: 10.1080/19442890.2016.1150627

Samaddar, A. (2006). Traditional and posttraditional: a study of agricultural rituals in relation to technological complexity among rice producers in two zones of West Bengal, India. *Culture Agricul.* 28, 108–121. doi: 10.1525/cag.2006.28.2.108

Schlosberg, D., and Caruthers, D. (2010). Indigenous struggles, environmental justice, and community capabilities. *Global Environ. Politics* 10, 12–35. doi: 10.1162/GLEP_a_00029

Schlosberg, D., and Collins, L. B. (2014). From environmental to climate justice: climate change and the discourse of environmental justice. *Wiley Interdiscip. Rev. Clim. Change* 5, 359–374. doi: 10.1002/wcc.275

Schneider, L., and Haller, T. (2017). "A region under threat? Climate change impacts, institutional change and response of local communities in coastal Yucatán," in *Climate Change Adaptation in North America: Fostering Resilience and the Regional Capacity to Adapt,* eds W. Leal Filho and J. M. Keenan (New York, NY: Springer International Publishing), 161–175.

Secretaria de medio Ambiente y Aprovechamiento Sustentable (2015). *Programa Estatal de acción ante el cambio climático: Vision 2015-2030*. Campeche: Gobierno del Estado de Campeche, 133.

SEMARNAT-INECC (2016). *Mexico' s Climate Change Mid-Century Strategy*. Mexico City: Ministry of Environment and Natural Resources (SEMARNAT) and National Institute of Ecology and Climate Change (INECC), 106.

Sharer, R. J., and Traxler, L. P. (2005). *The Ancient Maya, 6th Edn*. Stanford University Press.

Singh, R., and Singh, G. S. (2017). Traditional agriculture: a climate-smart approach for sustainable food production. *Energy Ecol. Environ.* 2, 296–316. doi: 10.1007/s40974-017-0074-7

Smyth, M. P., Dunning, N. P., Weaver, E. M., van Beynen, P., and Zapata, D. O. (2017). The perfect storm: climate change and ancient Maya response in the Puuc Hills region of Yucatán. *Antiquity* 91, 490–509. doi: 10.15184/aqy.2016.266

Terán-Contreras, S., and Rasmussen, C. H. (1995). Genetic diversity and agricultural strategy in 16th century and present-day Yucatecan milpa agriculture. *Biodivers. Conserv.* 4, 363–381. doi: 10.1007/BF00058422

Terán-Contreras, S., and Rasmussen, C. H. (2008a). *La milpa de los Mayas*. Merida: Centro Peninsular en Humanidades y Ciencias Sociales, Universidad Nacional Autónoma de México y Universidad de Oriente, 396.

Terán-Contreras, S., and Rasmussen, C. H. (2008b). *Jinetes del cielo maya: dioses y diosas de la lluvia en Xocén*. Merida: Ediciones de la Universidad Autónoma de Yucatán.

Trench, T., Larson, A. M., Libert Amico, A., and Ravikumar, A. (2018). *Analyzing Multilevel Governance in Mexico: Lessons for REDD+ From a Study of Land-Use Change and Benefit Sharing in Chiapas and Yucatán*. Working Paper 236. Bogor: CIFOR.

Tsosie, R. A. (2007). *Indigenous People and Environmental Justice: The Impact of Climate Change, Vol. 78*, University of Colorado Law Review, 1625–1677. Available online at: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=1399659

Tuz-Chi, L. H. (2009). *Así es nuestro pensamiento. Cosmovisión e identidad en los rituales agrícolas de los mayas peninsulares*. Universidad de Salamanca.

Valencia-Rivera, R. (2017). El tiempo vuela : el uso de aves y otros animales para representar las unidades de tiempo de la cuenta larga maya. *J. Soc. Am.* 399–428. doi: 10.4000/jsa.15310

Vázquez-Domínguez, E., and Arita, H. T. (2010). The Yucatan peninsula: biogeographical history 65 million years in the making. *Ecography* 33, 212–219. doi: 10.1111/j.1600-0587.2009.06293.x

World Bank (2018). *Realigning Agricultural Support to Promote Climate-Smart Agriculture. Agriculture Global Practice Note*. Washington, DC: World Bank.

Zizumbo-Villarreal, D., Flores-Silva, A., and Colunga-García Marín, P. (2012). The archaic diet in Mesoamerica: incentive for milpa development and species domestication. *Econ. Bot.* 66, 328–343. doi: 10.1007/s12231-012-9212-5

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.