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RESEARCH ARTICLE

Recalcitrant maize: Conserving agrobiodiversity in the era of genetically modified organisms

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Societal Impact Statement

The problem of genetically modified maize contamination in Mexico is the result of both planned and unplanned consequences of scientific and political choices. We show how a risk management strategy based on the modernist dichotomy between “modern” and “native” has failed to protect Mexican landraces and has marginalized other forms of knowledge that are urgently needed to understand and support the fluidity of Mexican biocultural landscapes. Farmers' seed systems are a fundamental source of crop resilience and evolution. They can constitute safe pathways for creating new maize varieties able to withstand climate and societal changes.

Summary

- In 2001, an alert on the contamination of Mexican maize landraces by genetically modified (GM) maize spurred new actions to conserve the world's biggest reservoir of maize genetic diversity. We analyze how the largest maize collection effort in Mexican history, and the definition of the conservation procedures employed in it, either involved or marginalized different approaches to this environmental problem.
- The article is grounded in the sociohistorical analysis of the controversy of GM maize contamination and brings together new historiographical perspectives on Mexican scientific and political interest in native maize. It also draws on ethnographic approaches, extended fieldwork, and analysis of data from Mexican government agencies.
- We show how different epistemological traditions have made the risk of GM maize contamination (in)visible and thereby generated normative choices. We illustrate how the GMO controversy brought the theme of native maize back onto the Mexican political and scientific agenda. The normativity that shaped the controversy in the 2000s influenced current knowledge and how the problem of GM maize introgression is still addressed today.
- The entanglements between biotechnology, native landraces, and farmers' practices are too dense to be “scientized” and kept separate to be made manageable as areas of purely technical “risk.” The result is a geography of maize infused with

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all sorts of temporalities and materiality, which escapes the bounds of technoscientific framings. This intricate environment-making process calls for new collaborations among epistemic cultures to tackle the possible consequences of GMOs for agrobiodiversity, seed systems, and their resilience.

KEYWORDS

agrobiodiversity, conservation, genetically modified organisms, maize, Mexico, risk, seeds

1 | INTRODUCTION

Mexico is one of the world's megadiverse countries and the center of origin and domestication of multiple cultivated plants (NCM, 2019). In particular, it is the center of origin of maize and the richest reservoir of maize genetic resources (Kato et al., 2009). Only between 20% and 40% of maize seeds planted each year in the country come from commercial hybrids: The majority of planted seeds are drawn from farmers' seed systems (Aquino et al., 2001; Donnet et al., 2012; Perales & Golicher, 2014). Smallholder maize production in Mexico is not one of households' main sources of monetary income but fulfills important food security functions within them (Bellon et al., 2018; Eakin et al., 2014; Rivera & Contreras, 2015). This is because native maize has continued to allow for agricultural responses to highly diverse "microenvironments" where hybrids are not a viable alternative (Bellon et al., 2018; Bellon & Hellin, 2011; Fenzi et al., 2017). Maize landraces help farmers deal with environmental and socioeconomic changes and mitigate climate risk (Bellon et al., 2011; Eakin, 2000; Mercer et al., 2012). In Mexico, farmers save, select, and share maize seeds (Bellon & Berthaud, 2004; Fenzi et al., 2021; Louette et al., 1997; Perales et al., 2003). For these reasons, farmers' seed systems are at the heart of the ongoing evolutionary process of maize diversity (Bellon et al., 2018; Perales, 2016). Mexico has a long tradition of scientific interest in maize diversity, in which competing and complementary frameworks—regulations on plant genetic resources, agricultural policies, and the biocultural dimension of crop diversity—are telescoped together.

Native maize in Mexico gained international scientific attention at the beginning of the Green Revolution, with the launch of the Rockefeller Foundation's first agricultural program in Mexico (MAP) in 1943 (Curry, 2022; Fenzi, 2017; Gutiérrez Núñez, 2020a; Méndez Rojas, 2018; Olsson, 2020). Between 1945 and 1955, the Office of Special Studies (OEE) organized systematic collections of maize populations.¹ Plant breeding was conceived as a "political technology." The foundation aimed to increase maize production as a means of political stabilization and a way to advance the North American political agenda (Perkins, 1997). For Mexican bureaucrats, "modern" agronomic science and technical assistance were tools to depoliticize agrarian reform and modernize the country. Breeders working on maize improvement took two main approaches: (1) dogmatically

reproducing US hybrid technology, through many cycles of self-pollination before crossing, and (2) developing various maize breeding strategies, such as synthetic varieties, using local materials to be effective across many environments (Fenzi, 2017; Gutiérrez Núñez, 2020b; Harwood, 2009; Matchett, 2002). Both strategies required breeders to assemble a stock of genetic material by collecting maize varieties and storing them in gene banks (Curry, 2017). Maize accessions were described and classified, and this process at once defined and was shaped by the concept of maize races (Curry, 2021). Maize became a scientific object and a cytogenetic model in its own right (Anderson, 1946; Anderson & Cutler, 1942; McClintock et al., 1981; Wellhausen et al., 1951). In the late 1950s and early 1960s, further efforts to increase collections were deemed no longer necessary. Scientific interest in maize germplasm declined, particularly within the International Maize and Wheat Improvement Center (CIMMYT), where breeders rarely used native materials for plant breeding. In the late 1960s, there was renewed interest in the exploration and conservation of maize landraces, following the global alert on genetic erosion and international germplasm conservation efforts coordinated by the FAO (Fenzi & Bonneuil, 2016). In 1967, more systematic work on collections was undertaken at the National Institute for Agricultural Studies (INIA) under the leadership of Abel Muñoz Orozco, the new head of the Chapingo Autonomous University germplasm bank, and the young agronomist Rafael Ortega Paczka. This reactivation of collection efforts was also due to the impact of the *Helminthosporium maydis* epidemic that was destroying US hybrid maize fields in 1970 and 1971 (Bruns, 2017).² Breeders and plant scientists then reconsidered the need for new collections to "update" maize varieties in the hope of obtaining genetic resistance (Fenzi, 2023). The collection campaigns started in the late 1960s were carried out as part of broader scientific efforts in a context of technological nationalism. This "Mexicanization" of research was accompanied by the condemnation of harmful side effects of the Green Revolution, together with a growing criticism of international development programs. Many agronomists began to document the widening gap between "modernized" and "traditional" agriculture and argued that Mexican agricultural research must be liberated from US techno-colonialism (Cotter, 2003). In the 1980s and 1990s, new nationwide collections for national breeding programs once again ceased to be a priority in Mexico. US interest in maize, however, did not decrease: In the

¹Funded from 1944 to 1960 by the Mexican Ministry of Agriculture and the Rockefeller Foundation.

²The use of plants carrying the Texas cytoplasmic male sterile (Tcms) trait made hybrids vulnerable to *Helminthosporium maydis* race T.

1990s, the US Department of Agriculture and seed companies promoted a cooperative project in 12 Latin American countries with the goal of identifying the best exotic germplasm (Salhuana et al., 1997) and providing new breeding lines to the American corn industry (Pollak, 2003).³ These new scientific and commercial programs coincided, in Mexico, with the government of President Salinas de Gortari (1988–1994), which launched new negotiations toward the North American Free Trade Agreement (NAFTA; now the USMCA).⁴ The implementation of NAFTA in the 1990s opened the door to massive imports of GM maize grains for both feed and human consumption. In 1996, in compliance with the NAFTA agreements, Mexico ratified the UPOV 78 Act approving a federal law on plant varieties (DOF, 1996). The issue of maize transgene finally burst dramatically into the public arena in November 2001, when Quist and Chapela's article in *Nature* reported the presence of transgenic DNA introgression in native maize in Oaxaca, Mexico (Quist & Chapela, 2001). This article provoked immediate and intense contestation, as well as counter-expertise (Delborne, 2008; Kaplinsky et al., 2002). For almost 10 years, scientists, some governmental agencies, and activists worked to raise awareness of the problem of transgenic maize dispersion and biosafety (Carreón-Zuñiga, 1994; Castro et al., 2006; Ezcurra et al., 2002; NRC, 1989; OECD, 2001; Serratos Hernández, 1996; Serratos Hernández et al., 1997). In a context of strong investment by both government and corporations in anti-regulation efforts, it took until 2007 before it finally became possible to publish the proof of the contamination of GM maize in its center of origin in peer-reviewed journals (Dyer et al., 2009; Piñeyro-Nelson et al., 2009; Serratos Hernández et al., 2007). The GMO controversy played a major role in the reactivation of the theme of native maize and the reintroduction of its conservation onto the Mexican political and scientific agenda (Álvarez-Buylla et al., 2013; Foyer & Bonneuil, 2015).

In this article, we analyze this most recent period of scientific interest in maize, focusing particularly on the last nationwide collection campaign undertaken as part of the institutional response to the GM maize contamination problem. We show that the results of this maize collection campaign, far from establishing a disciplined coexistence between native and GM maize, made possible a new, still incomplete geography of maize diversity in Mexico. We illustrate how this environmental problem has influenced, and been influenced by, the ways in which maize has been understood as a scientific and political object, and its existence in the Mexican social space justified. First of all, we trace the *historical ontology*⁵ of this problem: how experts brought it into existence as a public problem and made it knowable. Second, we study how certain approaches have gained more legitimacy than others, analyzing how the issue of transgenic maize contamination has been “framed” through expertise and political processes. How has it been defined in the scientific and

political arena? What sorts of relationships to nature, modernity, and tradition feature in these approaches? Looking at these questions allows us to investigate the definition of categories and the demarcation of their boundaries (i.e., GMO maize vs. native maize, traditional vs. industrial agriculture).

The notions of perceptibility and imperceptibility can be useful to describe the way objects or phenomena come to exist in the scientific and political world. For example, they have been used to analyze the scientific activism of US Environmental Protection Agency scientists investigating chemical exposures in offices in the 1980s (Murphy, 2006). These scientists were confronted with the failure of the methods and instruments used to establish risk regulations and standards. Furthermore, their ability to communicate their findings was restricted in a context heavily influenced by state and corporate interests. Supporters of deregulation can also take advantage of these difficulties to produce an opposing discourse devoted to minimizing or denying risks, a strategy that has been largely deployed and reported in other controversies, such as tobacco and chemical products (Oreskes & Conway, 2011; Rainhorn, 2019). Mexican scientists were facing similar difficulties, both in terms of techniques employed to prove the contamination and in terms of the production of uncertainty and imperceptibility generated by scientific and legal practices influenced by agribusiness. The approaches taken by different epistemological traditions to perceiving, or not perceiving, the risk of GM maize contamination have generated normative choices (Jasanoff, 2006, 2011), which have influenced the place of maize in Mexican agroecosystems and society. This regulatory knowledge serves to naturalize the presence of transgenes and expand tolerable limits (Boudia & Jas, 2014). At the same time, an opposite process can be seen in the trajectory of this issue: The interconnections between biotechnology, native landraces, and farmers' practices are far too dense and intricate to be fully “scientized” and kept separate to manage “risk” understood as purely technical (Kinchy, 2012; Wynne, 2001). The result is a geography of maize with expansive borders that overrun the boundaries laid down in technoscientific framings. This web of life shows an intimate and entangled dynamic between humans and nature in an environment-making process (Moore, 2015).

2 | BRINGING MAIZE CONTAMINATION INTO EXISTENCE

Mexico played an active role in the establishment of the Convention on Biological Diversity (CBD) in 1992. The convention commits the signatory countries to developing measures to protect biodiversity, the responsible use of biotechnology, and the precautionary principle. In 1993, when the risk of introgression of GM maize first surfaced, an ad hoc group of scientists from different disciplines was established (Carreón-Zuñiga, 1994): the National Agricultural Biosafety Committee (CNBA), which later became the Intersecretarial Commission on Biosafety and Genetically Modified Organisms (CIBIOGEM). This ad hoc group worked on regulatory instruments to protect maize

³See the Latin American Maize Project (LAMP) and the followup Germplasm Enhancement of Maize project (GEM).

⁴On July 1, 2020, the United States-Mexico-Canada Agreement (USMCA) (called T-MEC in Mexico) replaced the North American Free Trade Agreement (NAFTA).

⁵This term is used to describe how a scientific object or topic is brought into existence through historically specific practices (in the laboratory, observing, calculating) that make it true and visible. See Daston (2000).

diversity from the potentially harmful introgression of genetic materials from GM organisms into wild relatives and landraces.⁶ In 1996, the first permission for GM maize field testing in Mexico was granted to CIMMYT in Tlaltizapán, in the state of Morelos. These field trials were closely supervised by the ad hoc group, which was in charge of establishing security norms (Serratos Hernández, 2009). Despite the scientific consensus on the need for stringent norms, they were progressively loosened from 1996 to 1998 in response to demands for various forms of deregulation.

Antonio Serratos, an agroecologist and biotechnologist, co-organized two conferences in 1995 and 1997 to discuss this issue and published the first reports addressing it (Serratos Hernández, 1996; Serratos Hernández et al., 1997, 2000). As a result of scientists' mobilization, in 1998, Mexico's Ministry of Agriculture suspended all permissions for field testing and commercial production of GM maize. The pro-GM industry counter-lobbied drawing new arguments from a government report suggesting that there was “no need for concern” about gene escape from transgenic maize (Martinez-Soriano & Leal-Klevezas, 2000). This study and its conclusions were, in turn, promptly contested as overly hasty (Nigh et al., 2000). When, in November 2001, Quist and Chapela's *Nature* article revealed the introgression of transgenic DNA into Mexican maize landraces cultivated in the mountains of Oaxaca (Quist & Chapela, 2001), the issue of maize transgene contamination burst onto the public stage. This sparked an instant and vigorous debate against Quist and Chapela's results. One response in *Nature* suggested that their “i-PCR sequences [were] all artefacts and not genuine transgenes” (Kaplinsky et al., 2002, p. 601). In light of growing concerns around the potential impact of GM maize on native landraces and wild relatives, the Mexican government responded by conducting a national sampling and by organizing scientific workshops with the support of the Organization for Economic Cooperation and Development (OECD). In November 2001, the OECD and the USDA organized an international conference entitled “LMOs and the Environment” (OECD, 2002) and published a report on maize biology (OECD, 2003). Results from Mexico-wide samples of maize obtained by the Department of Agriculture and the National Institute of Ecology (INE) supported Quist and Chapela's findings (Alvarez-Morales, 2002; Ezcurra et al., 2002; INE-CONABIO, 2001). In 2002, the Commission for Environmental Cooperation (CEC, 2004), a body created under NAFTA to address a broad range of environmental concerns, affirmed the presence of transgenes, along with other governmental and non-governmental organizations (CEC, 2004; Herrera et al., 2002; Serratos Hernández, 2009).

In a second phase of the controversy, spurred by an article published in PNAS (Ortiz-García et al., 2005) failing to detect any transgenes in landrace maize, government and industry actors counter-lobbied on the basis of the idea of reversibility, claiming that the transgenes do not remain in the environment (Bonneuil et al., 2014; Foyer, 2010). Starting from 2006, the moratorium was

progressively lifted, and in 2009, experimental GM maize field trials were officially authorized within the legal framework of the Law on the Biosafety of Genetically Modified Organisms (DOF, 2005). This new opening was created despite various peer-reviewed publications reporting the presence of transgenes in several Mexican states, including in unauthorized locations (Dyer et al., 2009; Piñeyro-Nelson et al., 2009; Serratos Hernández et al., 2007) (Figure 1).

Farmers' seed systems are still the principal source of seeds in Mexico (Bellon & Hellin, 2011; Perales et al., 2003; Perales & Golicher, 2014). Maize is grown under open pollination conditions, where it is difficult to isolate different populations or varieties. Maize is a cross-pollinated species, and farmers deliberately mix commercial and traditional varieties to modify their morphologies and growing cycle (Perales et al., 2003). However, cross-pollination also often occurs involuntarily, mixing commercial and traditional varieties, giving rise to a phenomenon of creolization (Bellon & Risopoulos, 2001). Maize has a dual nature: it performs plasticity transforming itself through both scientific and peasant practices, but at the same time, maize is recalcitrant—defined by the Merriam-Webster dictionary as “obstinately defiant of authority or restraint.” Maize is uncontainable: It goes everywhere, following human practices while not respecting norms or boundaries. If transgene seeds are available, they can easily disperse producing unknown effects on maize biology and the environment (Agapito-Tenfen & Wickson, 2018; Bellon & Berthaud, 2006; Duncan et al., 2019; Dyer et al., 2009; Mercer et al., 2008, 2012; Serratos Hernández et al., 2004). In 2013, a successful collective lawsuit (Tello & Hernández, 2015)⁷ led to permits for the experimental and commercial planting of GM maize being halted or revoked (Figure 2), undermining decades of lobbying by multinational corporations such as Monsanto, DuPont Pioneer, and Dow AgroSciences to market their GM maize varieties in Mexico (Vargas-Parada, 2014). The government of Andrés Manuel López Obrador (AMLO) (2018–2024) has substantially increased precautionary legal measures to prevent the planting of GM maize. In February 2023, the government issued a presidential decree phasing out glyphosate and ordering that existing “permits to release genetically modified maize seeds into the environment on the national territory” be revoked and no further permits issued, nor “authorizations for the use of genetically modified maize grains for human consumption.” (DOF, 2023). Since 2013, the strategy of the Mexican government has been to prohibit the cultivation of transgenic maize but to authorize imports. This new decree marks a potential important change, but its implementation remains controversial. It is very difficult for Mexico to circumvent its legal obligations under the USMCA, and Mexico still imports over 17 million tons of maize annually (SIAP, 2022), mainly as animal feed from countries such as the United States, where GM maize is not systematically regulated and labeled (Dyer et al., 2009). The highly politicized regime of (im)perceptibility that the AMLO government established around the GM maize market does not focus on the study of the impact of GM maize contamination. The real situation regarding the introgression of GMOs in the Mexican landscape is thus still unclear, and the data

⁶In 1996, they published the Mexican Official Standard (NOM-056-FITO-1995) establishing the phytosanitary requirements for the transport within Mexico and the import of organisms manipulated by genetic engineering, and for the establishment of field tests for such organisms.

⁷Precautionary measure issued by the 12th Federal District Court (FDC, 2013).

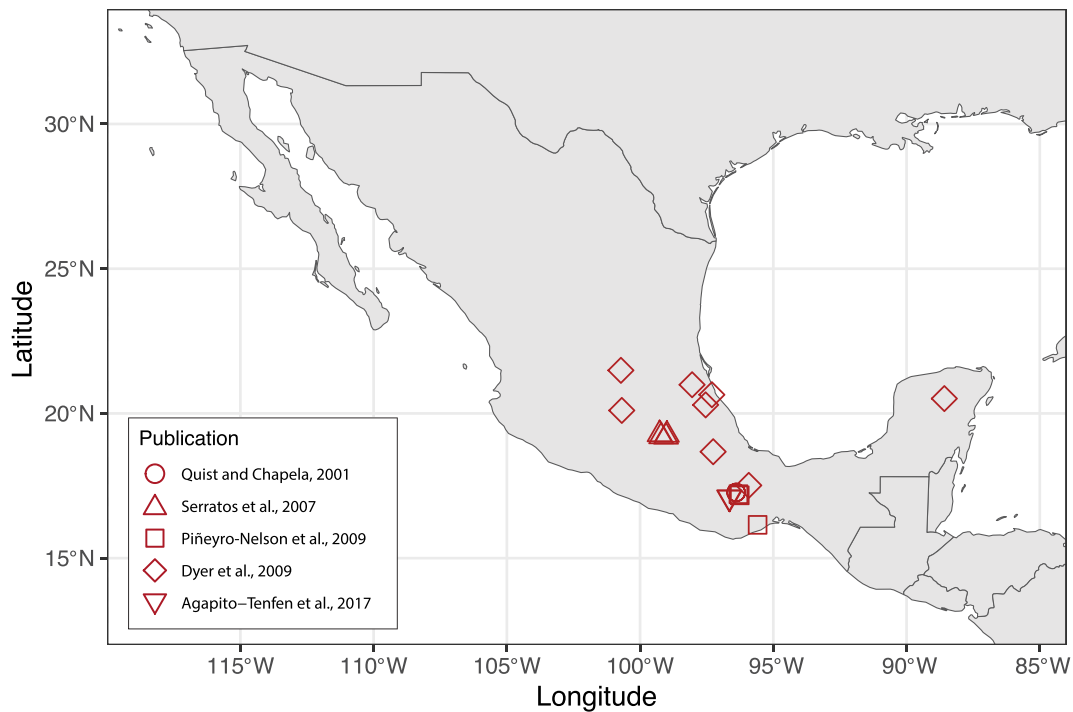


FIGURE 1 Detection of transgenic materials in Mexican maize landraces. Localities where transgenic materials were detected in Mexican maize landraces are depicted in red. Different shapes represent data extracted from different published studies (Agapito-Tenfen et al., 2017; Dyer et al., 2009; Piñeyro-Nelson et al., 2009; Quist & Chapela, 2001; Serratos Hernández et al., 2007).

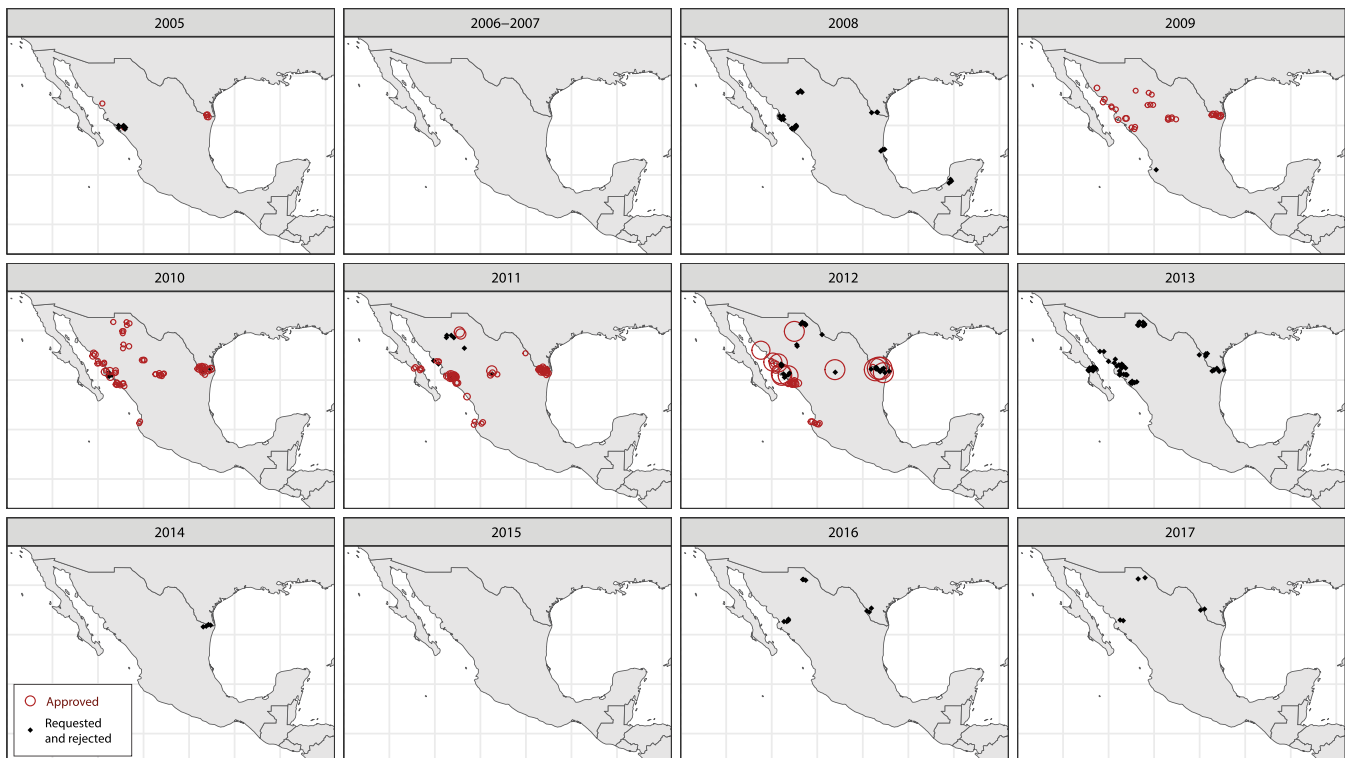


FIGURE 2 Requests for experimental and commercial planting of genetically modified maize between 2005 and 2017 across Mexico. Black diamonds indicate rejected requests and red circles indicate approved requests. The size of the circles is proportional to the surface allocated. Analysis of data obtained from CIBIOGEM (<https://conacyt.mx/cibiogem/index.php/solicitudes/permisos-de-liberacion>).

yielded by government agencies' monitoring remain, with few exceptions (Álvarez-Buylla, 2018), mainly unpublished.

The debate over the identification of transfers of genetic constructs to plant genomes has been scientized, with molecular biology considered the only valid form of evidence (Bonneuil et al., 2014). However, confirming the presence (or absence) of transgenes in Mexican landrace maize has by no means been a linear, straightforward process. Southern blot and PCR amplification of DNA, used in the 2000s, yielded contradictory results, including both false positives and false negatives (Piñeyro-Nelson et al., 2009). These difficulties resulted from several factors. First, due to commercial secrecy, DNA sequences in GM constructs are often absent from public repositories, making it more difficult to identify them. Second, the search for transgenes was based on the assumption that only a small number of genetically uniform maize types should be used as a control to compare amplified target sequences as a “reference genome.” This standard was employed to test the Mexican landraces. The assumption was made that a single “native plant”—a perfect maize ideotype—could and should be used as a control. This implied the assumption that landrace maize should behave similarly to commercial hybrid types, which are homogeneous and simple to sample, or to “ancestral” maize specimens used in archaeobotanical studies to study ancient gene flow (Kistler et al., 2020). This ideal control is not in fact applicable to the Mexican case, where native maize is subject to a continual evolutionary domestication process, and maize genomes are characterized by a complexity that conventional testing criteria based on homogeneous material are not designed to handle. And yet the inapplicability of these techniques in the Mexican case did not prevent them from being used. Scientists working to make the contamination visible struggled to adapt PCR methodology to their unconventional maize material, and the industry used this fuzziness to build doubt and advocate for the moratorium to be lifted. This struggle around the (im) perceptibility of maize contamination shows how the designation of what does and does not deserve to be seen determines what is knowable or unknowable and how control over this determination can be used to pursue specific goals. Every discipline and epistemological tradition is deeply invested in producing not only visibility but also invisibility (Oreskes & Conway, 2011; Rainhorn, 2019). While the state was committed to reassuring the public that everything was under control, professional experts, citizens, and international NGOs organized a mobilization against GMOs. The alarm was first raised in a milieu of scientists, intellectuals, and farming activists in Mexico City. It is in this context that the sense of a looming threat to Mexican biocultural heritage was conceptualized and made visible, before eventually being transferred to the countryside, where the majority of farmers had not perceived it and were generally silent. Ignacio Chapela, a microbial ecologist and one of the authors of the 2001 *Nature* article, recounted this process, saying that he felt somehow responsible for opening up a difficult process whose asymmetries were immediately evident:

We knew it was going to happen here one of these days, so it was a matter of gathering information and being prepared. To farmers in the communities, it

didn't mean anything. Then the article in *Nature* came out. It was a very complicated process because it's like when I tell you that something very serious has happened to you and you say “I don't feel anything, I don't see anything, I look at myself in the mirror and I am still the same.” They said to me: “You told us that something was happening, now tell us what is going to happen, if it is good or not,” and I would say “I don't know.” People in the mountains would ask me, “Is because of that that my dog died?” “What should we do?” and I would say “I don't know.” Reporters and documentary filmmakers were flocking to them, and they were asking them how they felt... for me, it was very difficult and dramatic because it was a very strong cultural intervention.

(Ignacio Chapela, personal interview, 2013)

3 | COUNTERING THE TURMOIL AROUND MAIZE THROUGH A NEW COLLECTION EFFORT

The GMO controversy directly and indirectly reactivated research on maize biological diversity and the valorization of native maize and triggered the development and implementation of public policies on these topics (Acevedo et al., 2016). Mexico signed the Cartagena Protocol in 2005 and ratified the Nagoya Protocol in 2012. Between 2006 and 2010, following the 2005 Law on the Biosafety of Genetically Modified Organisms (LBOGM), the government undertook a series of initiatives in this domain. The “Global Native Maize Project” (CONABIO, 2011) launched new collection campaigns to assess the status of Mexican maize diversity and to take measures for its conservation. The overall project is managed by the National Commission for the Knowledge and Use of Biodiversity (CONABIO), in coordination with the National Institute of Ecology (INE) and the National Institute of Forestry, Agriculture and Livestock Research (INIFAP).⁸ Three main categories of actions have been carried out: (1) a project of recompilation and analysis of the existing bibliography on the origin and diversification of maize (Kato et al., 2009); (2) a project of systematization and dissemination of information regarding maize and teosinte collections stored in INIFAP's Germplasm Bank in Jalisco; (3) 10 collection projects covering most of the maize-growing areas that had not been sufficiently surveyed. This is the most significant collection effort in Mexican history, doubling the number of collections in the banks and completing previous collection information (Figure 3).

The head of the INIFAP Gene Bank, Juan Manuel Hernandez Casillas, summarized the collection process as follows:

⁸It is funded by the Ministry of Environment and Natural Resources (SEMARNAT), CIBIOGEM, and the Ministry of Agriculture, Livestock, Rural Development, Fisheries, and Food (SAGARPA).

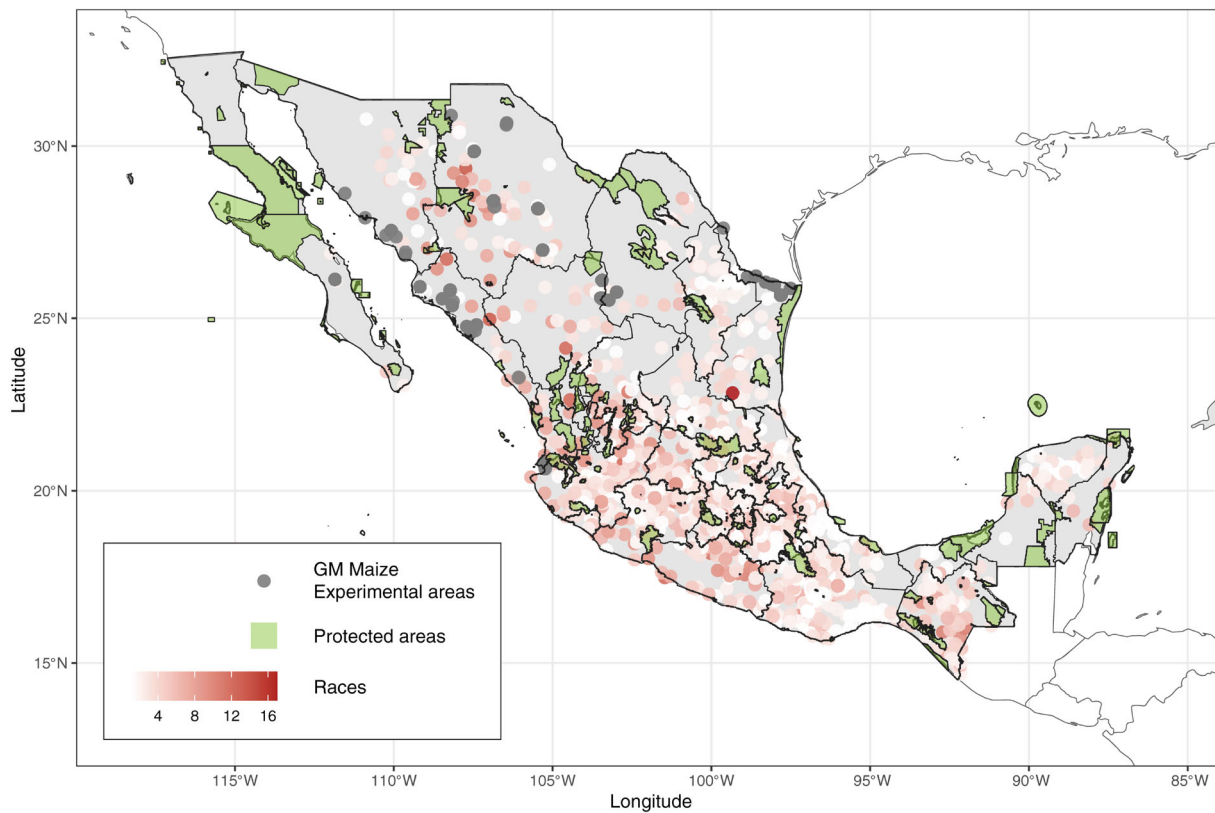


FIGURE 3 Distribution of sites of collection of native maize, protected natural areas, and genetically modified (GM) maize experimental planting in Mexico. Red dots indicate collections of native maize. Color intensity is proportional to the number of different races collected per municipality. Grey dots depict obtained requests for experimental planting of GM maize in Mexico from 2005 to 2017. Green areas represent protected natural areas. Data obtained from CONABIO, 2010 (<https://www.biodiversidad.gob.mx/diversidad/proyectoMaices>) and ANP, 2017 (http://www.conabio.gob.mx/informacion/gis/?vns=gis_root/region/biotic/anpnov17gw).

The INIFAP seed bank contains about 16,000 maize accessions from all over the country, from the 1950s to the present. Between 2004 and 2009, we collected 6,150 samples from all over the country, which allowed us to make progress in the study of the diversity within this species. This last collection has the particularity of constituting a quite homogeneous database. We know where the collections come from, the altitude they are grown at, who grows them, etc. Xolo [Efraim Hernández Xolocotzi (Xolocotzi, 1985)] could not participate in all the collection missions, others sometimes replaced him. That is why many of our oldest collections do not have a classification: those who participated in such collections were not always able to identify them. On the other hand, the collections that were done by Xolo, Paczka [Rafael Ortega Paczka] and all those who were trained by Xolo are complete in terms of classification. These collections were linked to breeding programs. In the 1970s, a genetic resources unit was created and to increase the diversity of accessions, the uncollected areas were given priority. Even today, the process of

searching for less represented areas and breeds continues.

(Juan Manuel Hernandez Casillas, personal interview, 2013)

The results of these recent efforts include updated diversity in the gene bank, the development of new databases, and a redefinition of the recognized centers of diversity (Kato et al., 2009; Orozco-Ramírez et al., 2017; Perales & Golicher, 2011, 2014). In addition, these new collections have shed new light on the distribution of maize diversity in relation to agricultural and social contexts (Lazos-Chavero & Chauvet, 2021). Perales and Golicher identified 11 regions of maize diversity and six biogeographic regions that possess more than 76% of the diversity, with the greatest diversity located in western Mexico (Perales & Golicher, 2011, 2014). A comparison of the genetic varieties found in these collections with previous ones shows that the distribution of diversity has not substantially changed. The biogeographic data show that no races have been lost, but highlight that less widespread landraces, due to their adaptation to particular agroecological conditions, maybe more subject to erosion phenomena (Perales & Golicher, 2014). This collection was also an opportunity for maize experts to reconsider the complexity of maize diversity in

Mexico in relation to scientific approaches. The collection methodologies and analytical framework applied to tracking maize diversity have remained almost identical since the beginning of collection efforts in the 1950s. Collections seek “all” diversity in a community, irrespective of abundance, and have never sought to register the presence of commercial cultivars, as these are not considered a part of native diversity (Perales & Golicher, 2014). This type of approach does not offer a more detailed view of the evolution of diversity and the emergence and/or transformation of new racial complexes. It also does not allow the specific distribution of commercial cultivars, and change in this distribution over time (its expansion or stasis), to be determined.

Juan Manuel Hernandez Casillas also raised questions about methods used to try and capture corn diversity:

Most of the accessions are maize that, in terms of classification, are similar to one or two races. To me, the races are nothing more than a reference point for understanding diversity. A question then arises. Should we include ambiguous samples, which “hesitate” between one or two races, or only accessions where one race predominates? We should then develop population-level genetics and conservation rather than race-level classification and genetics.

(Juan Manuel Hernández Casillas, personal interview, 2013).

The results of the collection also led to the overturning of dogmas, such as the idea that the north of the country is very poor in maize diversity. Of the 56 native races described nationwide, 32 are found in the northern regions (Lazos & Chauvet, 2012). Another example is the distribution of maize diversity on the territory, which is often associated with the presence of indigenous groups. The results showed that the factors underlying high diversity are more complex, and they are associated with the presence of peasant agriculture in general (Perales & Golicher, 2011). CONABIO's collection campaign ultimately showed that native maize exists throughout the country. Here, the application of science-based regulation to govern a risk (Boudia & Jas, 2014; Lascoumes & Le Galès, 2007), far from being a means of developing conflict-free solutions, drove the scientific and political controversy around maize. Knowing the distribution of native maize “by the numbers” (Desrosières, 1998) was the means chosen by the state to create equivalences and manage the problem. This large-scale effort to quantify maize diversity was intended to allow SAGARPA to divide the country into two different zones where distinct regimes would apply. Conservation and protection measures would cover areas with the presence of native maize, while in areas free of native maize, the naturalization of technical risk (Boudia & Jas, 2014; Fressoz, 2012) would allow the acceptance of GMOs. The 2005 Biosafety Law attempted to establish a framework for coexistence between transgenic and native maize (Acevedo et al., 2016; Foyer & Bonneuil, 2015), but the results of the collection effort provided a basis for challenging the establishment of such a dual regime. CONABIO advocated for the entire

territory of the republic to be recognized as a center of origin and diversification, with generalized protection through a total ban on the commercial planting of transgenic maize.

4 | MAIZE DIVERSITY SEEN THROUGH THE PRISM OF CONSERVATION POLICIES

Among the government initiatives designed following the GMO controversy⁹ was the Native Maize Conservation Program (PROMAC), coordinated by the National Commission of Natural Protected Areas (CONANP).¹⁰ PROMAC was one of the few programs worldwide for in situ/on-farm conservation of cultivated biodiversity (Foyer & Fenzi, 2021). It operated between 2009 and 2016 in designated protected natural areas (ANP) and aimed to conserve native maize races identified through collections (Mota Cruz & Orozco, 2021) (Figure 3). The program operated via a system of direct subsidies to farmers that represented 80% of the program's total budget, with the remaining 20% used for community capacity-building activities.

One of the particularities of PROMAC was that its activity was conducted in natural reserves traditionally devoted to the conservation of so-called wild diversity. Agricultural practices have generally been perceived as potentially harmful to the conservation of natural ecosystems. PROMAC legitimized peasant agriculture in protected natural areas, and farmers perceived it as a subsidy in “recognition” of their beneficial agricultural practices (Foyer & Fenzi, 2021). For their part, CONANP technicians used the program as an instrument to green agricultural practices within the reserves. For example, the use of herbicides was prohibited in order to “strengthen the *milpa* system.” The *milpa* is a traditional Mesoamerican polyculture that combines maize, beans, and squash and has become emblematic of sustainable agriculture. This combination of crops connected to traditional agriculture is sometimes dogmatically sought out by scientists.¹¹ The director of the La Sepultura Biosphere Reserve in Chiapas explained how this idea limited the expansion of the program: “The leaders of the program are looking for the ‘milpa indígena’ and if there are no indigenous communities, there can be no program!” (Alexer Vázquez, pers. comm., 2012).

From its launch in 2009, the approaches and objectives pursued in PROMAC were in constant evolution. The scientists, technicians, and administrators involved at each stage modified it according to their priorities and their intellectual and professional environment (Foyer & Fenzi, 2021). Two main visions were opposed: The first was that of the CONANP administration, which wanted to respond to the obligation to conserve native maize through direct subsidies to farmers. The second coincided with the world of “Mexican social

⁹SAGARPA has implemented various projects (through SINAREFI and SNICS) in collaboration with the “Red maíz” (maize network), composed mainly of native maize experts. They have pursued various aims, such as the networking of information on maize conservation, support for community activities such as *ferias de semillas* (seed fairs), and community seed banks.

¹⁰Programa de Conservación de Maíz Criollo, Comisión Nacional de Áreas Naturales Protegidas (CONANP, 2016).

¹¹Farmers often tend to maximize their effort in *milpas* by growing only maize, or by creating other systems as needed.

environmentalism” (Foyer & Dumoulin Kervran, 2013), composed of scientists and associations who aimed to implement more political initiatives to valorize criollo maize. This latest reconfiguration of the program did not find favor with the CONANP administration. One official explained: “The *in situ* conservation money allocated to the community is used for photo books and meetings; it is complicated because PROMAC is defined as a social program” (José Juan Arriola Arroyo, pers. comm., 2013).

In terms of Mexican policies in response to the problem of contamination, PROMAC contributed to breaking down the contraposition between the conservation of so-called wild and cultivated biodiversity. It worked as an environmental counterweight to productivist policies and helped to legitimize peasant agriculture. At the same time, the approach taken in the program reflects the risk management of the controversy over transgenic maize, which initially aimed to establish coexistence by separating protected areas with native maize from others with GM maize cultivation. Although this coexistence was rejected because CONABIO's collections showed that the whole country is a reservoir of native maize, the divide between modern productive agriculture and peasant agriculture has nonetheless shaped the associated conservation efforts. Peasant agriculture exists for the state “only” because it can be framed as a guardian of the genetic diversity of native maize and not for its productive role. PROMAC has supported 33,584 ha of *in situ* conservation in 69 priority areas (CONANP, 2016), but nationwide, it has involved less than 1% of farmers growing native landraces (Perales, 2016). Its impact on the conservation of native maize varieties is therefore limited compared to existing *de facto* conservation.

5 | CONCLUSION

The state's efforts to organize the maize landscape for purposes of control (Scott, 1998) have involved the imposition of particular approaches that tend to obscure the biocultural dimensions of the dynamics of maize diversity and the associated gene flows. With the adoption of a risk management strategy based on the modernist dichotomy of modern varieties/innovation acceptance versus native maize/genetic resource conservation, other forms of knowledge that can shed light on the fluidity of Mexican landraces were marginalized. This project originated from a dogmatic idea of races, according to which it is viable and desirable to isolate some “authentic” native maize in protected areas, while modern varieties, including GMOs, represent pure innovations that can be isolated in modern spaces. The maize “ideotype” model chosen by the government obscures the recalcitrant nature of maize diversity and, as a result, has produced unrealistic policy.

From the point of view of international regulations, the responsibility for conserving the largest reservoir of maize genetic resources for the future of agriculture lies with the Mexican government. More than 20 years after the beginning of the controversy, the issue of maize conservation in its center of origin is far from settled. The first phase of the controversy, in which competing actors worked on

different regimes of perceptibility and imperceptibility, paved the way for specific normative choices and environment-making processes. These processes are not mutually exclusive, and they coexist *de facto*, producing new genetic landscapes. The Mexican government has sought to frame the complex interplay between native maize and the products of industrial agriculture in standard risk management terms (Wynne, 1989, 1992). However, analyses of maize samples from across Mexico show that no location can be protected from the introgression of genetic constructs into landraces if GMOs are present in the country (Figures 1 and 2).

The national monitoring of GM maize, and the study of the resulting data, can provide an important understanding of an untackled problem (Ureta et al., 2023). The current political circumstances in Mexico are favorable for work on this problem, given the government's clear anti-GMO position. But there is a dearth of studies making this issue visible and knowable. If contamination is widespread, and the new genetic constructs have already been integrated into farmers' seed systems, how should the problem of contamination be reframed? How can awareness of a problem that is still invisible to farmers be created? We agree with Mueller and Flachs (2022) that portraying GMOs as a natural next step in domestication creates a false analogy that fundamentally misrepresents the processes of domestication, crop breeding, and the fabrication of GMOs. This narrative obscures the potential negative effects of gene constructs on the environment and farmers' seed systems. It can also hide the negative impact of industrial agricultural technology in terms of dependency on chemical inputs, intellectual property rights over seeds and ushering farmers into a spiral of technological fixes. The introgression of transgenes in Mexican landraces needs to be understood and tackled, focusing on changes in landraces and addressing the possible effects on farmers' seed systems, their resilience, and the social relations that depend on them. Farmers use multiple sources of seeds, and they generally do not make a rigid distinction between what is modern and what is traditional. They have multiple and local ways of describing and managing maize diversity. The modernist separation between hybrids, natives, and GMOs are categories constructed in other (scientific, political) spaces. Farmers' maize cultivation usually occurs in small plots situated close to each other and is based on systems of seeds flowing in and out of communities. Under peasant agriculture, the categories of commercial and traditional variety (or cultivar, landrace, and race) do not have effective boundaries. This is an uncontainable process. Similarly, maize itself is uncontainable and recalcitrant to industrial and administrative schemes. The ideology of managing each biological, social, and economic process in controlled and separate ways has failed and showed its inconsistency with maize and its cultivation in Mexico.

The difficulty of recognizing the recalcitrance of dynamics of maize diversity based on both biological and human dimensions has hindered the emergence of new configurations of epistemological traditions and techniques that could help understand maize gene flows and biosocial entanglements. Borrowing Donna Haraway's idea of “staying with the trouble” (Haraway, 2016), we do not need either to resign ourselves to a catastrophic end for biocultural diversity or

to expect to be able to conserve it by segregating places, varieties, and agricultural practices from each other. In the context of an intricate dynamic of crop diversity that is infused with all sorts of temporalities and materialities, we need approaches that can embrace this connectivity while enabling responsible approaches to the consequences of different kinds of human actions. These approaches must be able to sustain farmers' seed systems in an interconnected landscape, allowing the promiscuity of maize to play a role in safe pathways to new genetic configurations and sources of resilience.

AUTHOR CONTRIBUTIONS

Marianna Fenzi planned the research, performed the analysis, and wrote the manuscript. All authors (Marianna Fenzi, Jean Foyer, Valérie Boisvert, and Hugo Perales) have conceived, read, and approved the manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the public domain from CIBIOGEM (<https://conacyt.mx/cibiogem/index.php/solicitudes/permisos-de-liberacion>) and from CONABIO (<https://www.biodiversidad.gob.mx/diversidad/proyectoMaices>).

ETHICS STATEMENT

The analysis was performed using publicly available data. Participants provided their informed consent for the interviews.

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