Transdisciplinary Interventions to Improve the Sustainability of Maize Agroecosystems: A Case Study from Mexico

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The municipality of Ahuazotepec presented a complex food insecurity scenario, mainly because there are limitations regarding food supply/local maize production and the inhabitants so their access to food can be disrupted quite easily. A transdisciplinary approach and methodology were adapted to analyze, design, implement, and evaluate an agricultural intervention to improve agroecosystems in the region using agroecological practices. The experimental results indicated that the application of agroecological fertilization management improved soil fertility indicators, grain yield, benefit-to-cost ratio, and the resilience of the system. For the intervention, when a transdisciplinary scheme in which collaboration between actors was intensified, the benefits are greater than in a conventional scheme, where only economic or in-kind aid is provided, even when based on similar practices.

Keywords: Sustainability, agroecosystems, transdiscipline, agroecology, food security.

1 Introduction

Agriculture encompasses all the activities through which human beings manage and transform natural resources to produce food and other goods. According to Gliessman [1], agriculture is a process that takes place in three dimensions: environmental or biophysical, economic, or techno-economic, and social or socio-political. This means agricultural systems are complex and dynamic, due to the interactions that occur between these dimensions, their elements, as well as the associated natural and human systems [2, 3].

Despite this complexity, most agricultural research and interventions tend to be structured and separated by disciplines and are oriented to specific outcomes of the system, such as yield or resistance to adverse factors. Achieving agricultural growth has been indeed important, given its role in increasing per capita income and reducing poverty and hunger in developing countries, leading to the economic transformation observed in the 20^{th} century, particularly during the Green Revolution [4]. However, this conventional agricultural intensification approach also caused adverse effects such as the contamination of water bodies, reduction of soil fertility, and loss of biodiversity [5, 6]. These unintended but serious consequences reflect the limitations of the hyper-specialization in which agricultural research and science have submerged, the lack of interaction and cooperation between scientific disciplines, as well as a prevalence of reductionist and non-systemic visions during the design of agricultural interventions [7–9].

In this context, Francis et al. [10] mentioned that, although disciplinary approaches and interventions are helpful in increasing production, they are inherently incompatible with the sustainability of the agroecosystem. In this case, sustainability means that both economic and social/human developments are promoted in a fair and environmentally compatible way [11]. For agriculture, ensuring that agroecosystems are sustainable means they have stable yields, are socially acceptable, are resilient to the effects of external factors, and prioritize the use of agricultural practices that preserve the natural resources used for production and have a low environmental impact [12, 13]. Thus, humanity needs to abandon the paradigm of "increasing yield at all costs" since increasing productivity is only the first step in improving the agroecosystem as a whole [4]. Additionally, it is worth remembering that achieving the Sustainable Development Goals requires combining the three dimensions of sustainable development: *economic, social, and environmental* to solve the most pressing problems of humanity, both in rich and poor countries. Sustainable agriculture is directly or indirectly linked to the goals centered on attaining food security, reducing hunger, improving nutrition, protecting the environment, reducing inequality, and promoting lasting, inclusive, and sustainable economic growth.

It is also necessary that in the present and the future, improvements and impact assessments in agricultural systems are approached from a holistic, systemic, inter, multi, and transdisciplinary perspective, to avoid negative trade-offs when an agroecosystem improvement is proposed. Agricultural research under a Transdisciplinary perspective can also overcome the disconnection between academia and social problems, integrating researchers with problem actors, in order to generate holistic knowledge that corresponds to reality and that solves problems of a complex nature [9, 14, 15]. The participation and knowledge of the actors are key to obtaining valid local diagnoses, defining specific research priorities, and helping in joint impact evaluations. Indeed, the FAO et al. [4] establish that such local and regional diagnoses are needed to assess the role of agriculture, direct the required interventions, guide the required interventions and sequence the measures that will be applied.

Considering all of the above, this article presents a case study where a Transdisciplinary perspective [15] was applied to improve the sustainability of the maize agroecosystem in a Mexican municipality via the design, implementation, and evaluation of a comprehensive agricultural management plan.

2 Methodology

2.1 Study Site Description

The research area is located in the municipality of Ahuazotepec (20° 00'06"- 20° 07'06" N and 98° 03'42"- 98° 10'24" W) in the state of Puebla, consisting of 21 communities as shown in Figure 1 [16]. The municipality is located in a high-altitude valley characterized by plateaus and mounts with varying elevations between 2000 and 2600 m above sea level. Soil is predominantly medium textured andosols, suitable for agriculture and livestock production. Ahuazotepec has two major rivers, the Totoloapa and the Tlachinalco, as well as intermittent creeks that join those mentioned and several springs used for drinking and agricultural irrigation. The climate is temperate and humid, with a rainy season in summer and a frosty-dry season in winter, with mean annual temperatures of 13.2 °C and 804 mm of total rainfall [17].

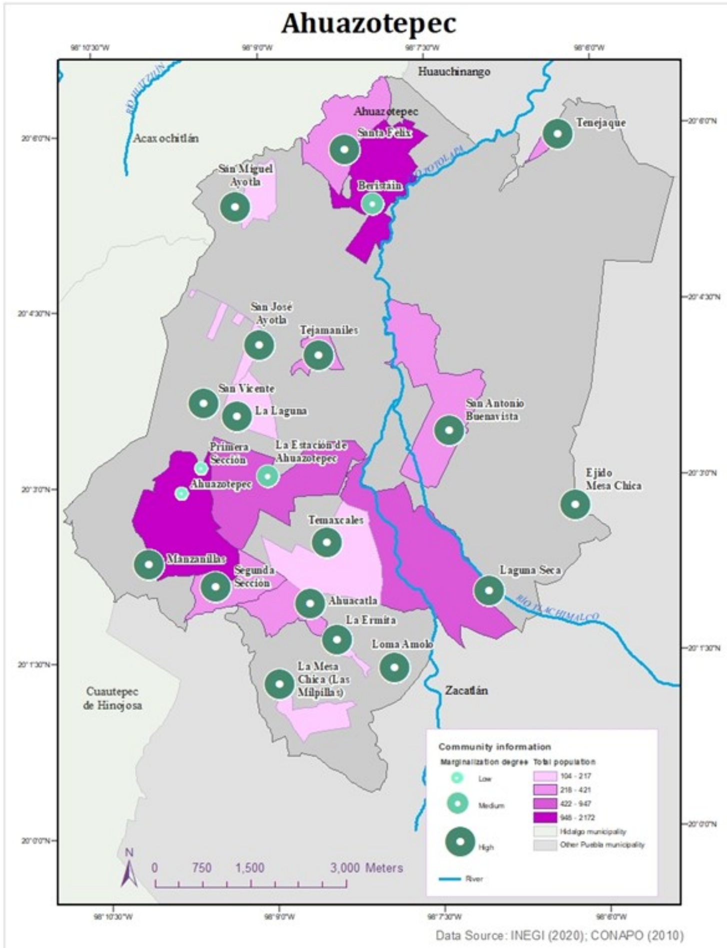

Figure 1: *Ahuazotepec municipality: Marginalization degree and population. Data taken from [18, 19].*

According to the most recent censuses, the population is 11,439 inhabitants (48.8% men, 51.2% women), with a median age of 25 years or less and an average household size of 4.1 people. Over half of the inhabitants live in the communities of Ahuazotepec, Beristáin and Laguna Seca [16, 19, 20] (Figure 1). Nearly 44% of the population is considered economically active 70% is engaged in agricultural activities [21].

2.2 Transdisciplinary Approaches to Real-World Problem Solving

There is a current trend toward reducing synthetic inputs in agricultural production, that is, making it more friendly to the environment and health [12]. However, these approaches must also consider the additional pressure of increasing productivity in regions with high yield gaps for staple crops such as maize [22, 23]. Thus, to close yield gaps, it is necessary to intensify agricultural production in a sustainable manner, rescuing and optimizing traditional agroecological practices.

This project was developed by applying the Transdisciplinary meta-methodology proposed by Hernandez-Aguilar [15] which consists of four stages or phases: (1) Research contextualization: to establish the baseline situation of the system, define the real-world problem and obtain evidence of it, and select response variables to monitor. (2) Solution proposal and experimental evaluation: to produce socially robust knowledge and ensure the solution is acceptable and feasible for the community; implies incorporating society and academia and integrating/adapting one or more scientific methodologies. (3) Implementation of the solution and impact assessment: actors are further integrated to assess the effects of the solutions and provide feedback for collaborative improvement. These phases exist within a framework of self-research and reflection (Phase 4) aimed to promote collaborative work and further interaction with the studied system and the actors [15, 24, 25].

The methodological framework was implemented as follows:

- Phase 1 and 4: The characterization of the municipality of Ahuazotepec, Puebla as a study system, was carried out by establishing its physical, temporal, productive, institutional, and socioeconomic limits and borders considering the existing information [26]. For the initial characterization, statistical data available through institutional sources on agricultural production in the municipality were collected. Additional information that was not available in institutional or academic databases was obtained using various participatory tools, such as surveys, focus groups, interviews, as well as consulting/interviews with local authorities and cooperating producers. Likewise, and in order to comply with the self-investigation framework, ethnographic research tools were used, mainly observation, dialogue, and reflection, in order to understand the behaviors and practices of the system under study and establish links based on empathy and identification with the actors that are part of it [27]. In this stage of the investigation, a modification of the Framework for the Evaluation of Management Systems incorporating Sustainability Indicators (Spanish acronym: MESMIS) was used. This framework is designed to be applied to agricultural, forestry and livestock systems, under collective or individual management [28]. This methodology was used to carry out a diagnosis of municipal sustainability which is detailed in Dominguez-Hernandez et al. (2018) [29]. This diagnosis made it possible to define critical points with which the scope of action was delimited, so that the most pressing specific problems are addressed and to establish the bases for the possible solution to be proposed and the measures that were taken in the interventions.
- Phases 2 and 3: During these phases, the experimental evaluation of the solutions and their effects on the previously defined response variables defined is required. In general terms, the intervention incorporates agroecological principles and practices to improve the production of maize grain. It was designed with an approach that involved collaborative work with the actors of the system including producers, academics, and the local government. Agricultural experiments were carried out at the plot level, to experimentally validate agroecological practices [30, 31] that would address the productivity limitations (critical points) of local agroecosystems. Finally, a management plan (intervention/solution) based on the results, was designed, proposed, and evaluated at a pilot scale to know its impact on the lives of local producers.

The following section presents in detail the results of the creation process, such as the results of the experimental evaluation of the solution, and its subsequent implementation at a pilot level in the municipality.

3 Results and Discussion

3.1 System Characterization: Maize Production

In the state of Puebla, as in the rest of the country, maize is the predominant crop and agroecosystem, since more than 80% of the cultivated area is dedicated to it.

It is considered essential for the food security of small producers since between 19.9 and 52.4% of grain production (960 thousand 406 t) is used for self-consumption [32]. This corresponds with the percentage of family subsistence units that make up 73% of the total rural production units in the country, which are mainly concentrated in the states of Mexico, Guerrero, Chiapas, Oaxaca, and Veracruz [32].

Accordingly, in Ahuazotepec the bulk of grain production is destined for self-consumption. And, as it is common in the municipalities of the Sierra Norte of Puebla, most maize grain is nixtamalized to produce tortillas. In Ahuazotepec, the agroecosystem is composed of a mixture of smaller systems, mostly characterized by low input use, low technology, and low yields. These conditions reflect those prevailing in the Sierra Norte de Puebla and in the country since maize is cultivated in agroecosystems that combine modern and traditional practices. According to data from the National Agricultural Survey [33] about rainfed production units: the majority use native or landrace seeds (61.7%), employ some type of fertilizer (24.3% organic, 67.4% chemical) and other agrochemicals (59% herbicides, 45.7% insecticides), but often lack access to mechanization for agricultural labors such as planting (29.2%) or harvesting (15.4%).

Although mean maize production is above the national annual per capita consumption (196.4 kg), in the years between 2010-2016 there was also a decrease in maize yield, despite the subsidies available to increase food productivity (PROGAN/PROAGRO, PROCAMPO). These state federal subsidization programs have been available since the 1990s but have clearly failed to increase maize yield in Ahuazotepec. This is because they are often applied late and do not contain training or agricultural extension components that help use resources more efficiently [29, 34].

Taking all this information into account, Ahuazotepec seems to present a complex scenario. There are limitations regarding local agricultural production, and agriculture-derived income, and, despite government efforts, the prevalence of poverty is high. This situation means that low-income households that depend on maize production, even if they are not classified as food insecure, may risk insufficient intake of nutrient-dense foods, making them vulnerable to suffering from malnutrition [35].

3.1.1 Addressing the Critical Points that Affect the Productivity of the Maize Agroecosystem in Ahuazotepec

According to the MESMIS analysis, two critical points were determined in this agroecosystem: chemical fertilization and weed control, which also correspond to 32 and 42% of production costs, respectively. But also have negative environmental impacts such as pollution due to lack of knowledge and training for their correct use. Additionally, producers lack opportunities to sell their landrace grains in more lucrative markets and often stop their cultivation in favor of more profitable but also more expensive varieties. The local diagnosis also brought more light to the effects of low productivity on the food security of farming families. On the one hand, the percentage of the producer's income derived from maize is less than 10%, which means they depend largely on non-farm income and on food-aid programs to supplement household income. On the other hand, low maize production reduces their food self-sufficiency, since 50% of farmers obtain yields below the municipal average and therefore cannot cover the basic needs of their families [29].

Even though the limitations described are big, it is possible to ensure the productivity of agroecosystems via the optimization of certain local production practices. Previously we identified [29] traditional producers with yields of 4 t per hectare, in systems where agroecological practices are used; these included the application of manure, the use of native seeds and adequate manual or mechanical weed control. These practices are based on traditional knowledge, and although the yield may be arguably moderate, they tend to be more stable due to low dependence on external inputs and the high agrodiversity within the production units [1, 12].

Regarding the use of agricultural inputs based on organic sources, the research group evaluated biofertilizers made with residues from livestock production and nixtamalization. Results of these experimental trials indicated organic sources produced average maize yields 2.1 tons higher than those obtained using chemical fertilization [30]. Additionally, in another experiment, the use of manure-based soil amendments and mulches was shown to lower the incidence of weeds in agroecological systems. This meant reduced the need for weeding and thus the agricultural workload while maintaining the benefit of collecting edible weeds/forage free of agrotoxic residues [31]. In addition, the recovery of nutrients contained in manure and other organic wastes allows mitigating the polluting potential of agriculture [36]. Also, the use of manure and wastewaters increased energy efficiency by 27% more than chemical fertilization [30]. In economic terms, organic fertilization generated a benefit-cost ratio up to 88% higher than conventional fertilization. Finally, to the benefits mentioned, these agricultural experiments reported that the agroecosystems where this type of fertilization or amendments are used become more resilient to adverse climatic phenomena.

3.1.2 Design, Evaluation, and Implementation of the Intervention

Considering the problems described in the previous sections, and based on the needs of the community, it was necessary to define, implement and evaluate a comprehensive management plan aimed at the sustainable improvement of the maize agroecosystem, and that would also increase the food security of participating producers. The results of experimental and pilot-level evaluations carried out to validate the application of agroecological practices in this agroecosystem are presented below.

3.1.3 Collaborative Experiment to Evaluate Agroecological Practices in the Yield of Creole Maize and Soil Properties

In data from a survey applied to 95 maize producers in the municipality of Ahuazotepec, Puebla, differences in the yield and incidence of pests and weeds were identified, particularly in units where agroecological practices are carried out (e.g., manure application). To establish whether the differences in these variables were caused by changes in the soil due to agroecological management, the research group established a controlled experiment in the production unit of a collaborating farmer scientist.

Design and Establishment of the Experiment: An experiment was established in the spring-summer cycle of 2017, in the "Rancho Laguna Seca" production unit. Three treatments were evaluated: Control (no fertilizer application), Sheep manure (25 t ha^{-1}) and Chemical (115 N-00 P-00 K, source: urea). The response variables or indicators were maize yield and soil properties. Each treatment was replicated three times; the experimental unit consisted of six furrows ten meters long and 0.8 m wide, considering the two central furrows as the useful plot. The preparation of the land consisted of mechanical ploughing and furrowing, followed by sowing. A landrace variety of dark blue or black Elotes cónicos maize obtained from producers in the area was planted. The planting date was May 12, 2017, and a planting density of 62,500 plants per ha was used.

Soil sampling was done before planting (April 20, 2017) and after harvest (November 10, 2017). The samples were taken at a depth of 30 cm, they were obtained from the central part of each experimental unit; they were dried in the shade, ground, and sieved with a 2 mm mesh. Nitrogen, phosphorus, and potassium were determined by reading with the c215 Grow meter. Master Basic (Hanna Instruments®), the percentage of organic matter with the Walkley and Black method, in addition, for each sample the apparent density was determined with the test tube method [37]. The performance was determined in t ha-1, considering a 12% moisture content, was calculated as: GY = (FW x% DM x% G)/8800 [38], where FW = cob field weight in kg; %DM = dry matter percentage; %G = percentage of grain.

Evaluated Indicators: Yield and Soil Properties: Grain yield presented significant differences between the evaluated treatments ($P = 0.04$). The plots where manure was applied had an average yield of 6.9 t ha^{-1}, where chemical fertilizer was applied 1.37 t ha^{-1} less were obtained and in the plots, without application, the average yield was 4.36 t ha^{-1} (Figure 2).

The results of the experiment are in accordance with those reported by Miron et al. [39], who obtained increases of 25% in maize yield in treatments with manure application compared to inorganic fertilization. Mucheru-Muna et al. [40] reported that the application of 6 t of bovine manure per hectare increased yield by 15% in soils with good fertility and 67% in poor soils compared to inorganic fertilization. Opala et al. [41] found that 6 t ha -1 of manure provided 60 kg ha^{-1} of nitrogen, increasing maize yield by 5% compared to treatments where the same amount of nitrogen was provided with urea. These results correspond to local reports where it was found that producers that use manure reported yields above 4 t ha^{-1}, while conventional management with chemical fertilizers decreases the maximum yield to 3.5 t ha^{-1} [29]. Additionally, weed problems were reported in 39. % of the units where manure was applied, while only 16% reported pest damage; both values were lower than those reported in producers that carry out conventional management (27.5% reported pests and 39.6% weeds).

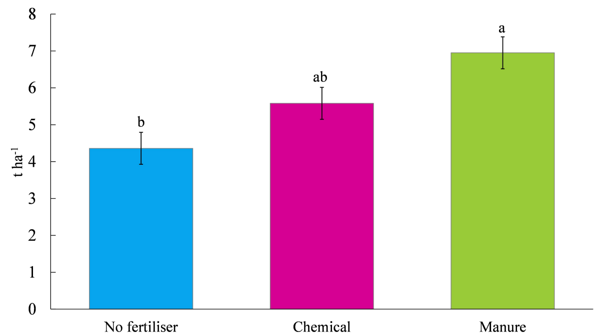

Figure 2: *Grain yield (t ha^{-1}) in Creole maize grown in Ahuazotepec, Puebla, PV-2017 cycle.*

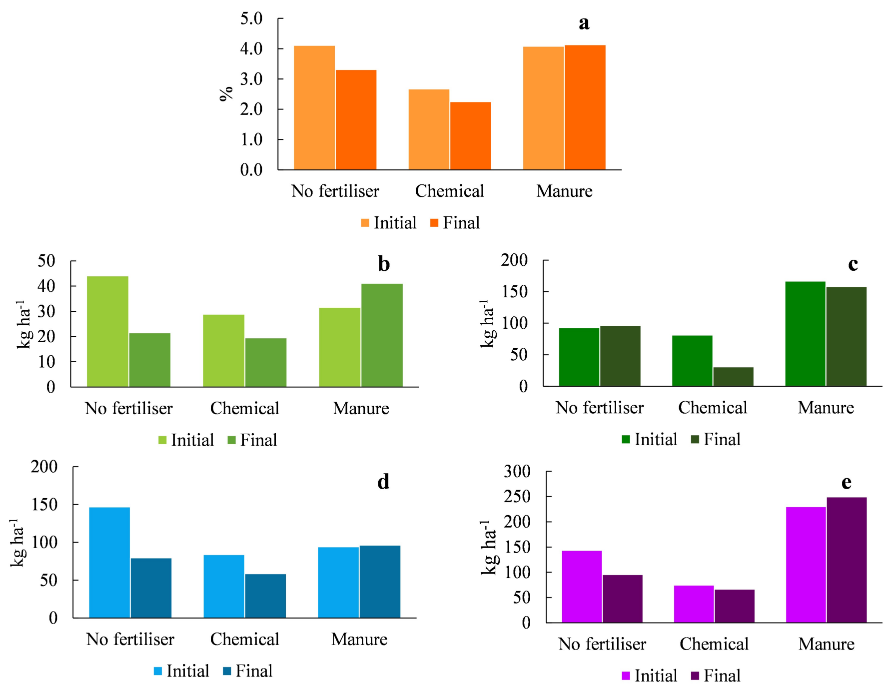

Figure 3: *Soil properties evaluated in creole maize cultivated in Ahuazotepec, Puebla, PV-2017 cycle. a: Organic matter content (%), b: Ammoniacal nitrogen (kg ha^{-1}), c: Nitric nitrogen (kg ha^{-1}), d: Available Phosphorus (kg ha^{-1}), e: Potassium (kg ha^{-1}).*

Organic matter content decreased in the control and chemical treatments by 0.8 and 0.4%, respectively. The treatment with manure had an increase of 0.05% during the cycle, results that agree with those reported by Meng et al. [42] and Wang et al. [43], as well as the trends reported by Salazar-Sosa et al. [44] and Trejo-Escareño et al. [45]. The differences found were not statistically significant (P = 0.869), however, the experimental units that have been managed conventionally and with the application of chemical fertilizers had the lowest organic matter content of the group (Figure 3a).

Ammoniacal nitrogen (NH_4^+ -N) increased 31% in the treatments with 25 t of sheep manure per hectare; the chemical fertilization units had a reduction of 9.4 kg ha^{-1}, while those where no fertilization was applied had a decrease of 22.6 kg ha^{-1} (Figure 3b). The differences were not statistically significant (P = 0.155).

The nitric nitrogen (NO_3^--N), reported in kg ha-1, decreased by 37.7% in the treatments with chemical fertilization and 5% in plots where manure was applied, the differences were statistically significant between the control and the chemical treatment (P =0.027), where the first had a (NO_3^--N) 3.6 units higher than the latter (Figure 3c).

A similar trend was found by Dinesh et al. [46] who obtained increases of between 45 and 48% using organic management with 66.6 t ha-1 of manure combined with neem, ash, vermicompost/microorganisms, and by Wang et al. [43] who report increases between 22.9 and 24.7% after three years of application of 52.5 t ha^{-1} bovine manure. Salazar-Sosa et al. [44] reported average increases of 330% with respect to treatments without fertilization. This was explained by the fact that Nitrogen content tends to increase when organic matter content is high since microbial activity favors its mineralization [43, 46].

The amount of phosphorus (PO_4^{-3}) decreased 30% in the units with chemical fertilizer application and 45.8% in the control; while manure treatments had an average increase of 2.2%, the differences found were not statistically significant (P = 0.584) (Figure 3d). This behavior coincides with that reported by [42].

Potassium content increased 8.4% in manure fertilization treatments, while control and chemical fertilizer units had a decrease of 33.5 and 10.1%, respectively (Figure 1e), the differences were not statistically significant (P=0.77). The first results coincide with those found by Salazar-Sosa et al. [47], who reported increases of up to 30.4 ppm in applications of 160 t ha^{-1} of manure with respect to the control treatment.

Taken together, the results indicated that agroecological practices improved soil quality. One of the main benefits of the use of organic fertilizers is the conservation or improvement of soil quality through the provision of organic matter, which in turn is related to greater stability and resilience in food production systems based on agroecological principles [12].

3.1.4 Intervention 2: Government Program to Increase the Economic Sustainability of the Maize Agroecosystem

In the municipality of Ahuazotepec, Puebla, according to data from a survey applied in 2015 [29], it was determined that the average yield of maize for grain of producers of the traditional self-consumption agroecosystem is 1.55 t ha^{-1} with a benefit-to-cost ratio of 22 cents for each peso invested, however, 50.9% of these producers did not cover the per capita consumption. Considering the critical points, it was determined possible to increase the economic sustainability of the system through the integration of agroecological practices and the modification of the conventional production process, to make more efficient use of resources for production.

Solution Design and Implementation: The intervention was co-created with the participation of academics from the research group, producers and the local Department of Agriculture, Commerce, and Industry. The initiative was presented to the Municipal Council, giving rise to the "Program to increase the economic sustainability of the maize agroecosystem in Ahuazotepec, Puebla". The program was implemented in the spring-summer production cycle of 2017. The objective of the program was to increase the economic sustainability of the maize agroecosystem in Ahuazotepec, Puebla through the establishment of experimental production units managed under a proposed technological package.

The selected production units were 26 (14 under irrigation conditions and 12 under rainfed conditions) and belong to maize producers in food vulnerability. Within the program, two approaches were used: the first where institutional participants and the producer worked in collaboration to carry out the activities inherent to the production process and apply the agricultural inputs provided (TS, Transdisciplinary Scheme, Figure 4), and the second, a scheme where agricultural inputs and technical advice are provided upon the producer request, but no further collaboration was expected (CS, Conventional Scheme, Figure 5).

The practices proposed and promoted included fertilization using manure (previously validated), split fertilization, mulching and soil amendments, application of mechanical cultivation to reduce the incidence of weeds, reduction in the use of agrochemicals, the application of emergency irrigation and the use of higher planting densities, among others [30, 48, 49]. In the CS, the producers were shown how to apply the

Figure 4: *Production of maize in Ahuazotepec Puebla under the "Program to increase the economic sustainability of the maize agroecosystem in Ahuazotepec, Puebla". Transdisciplinary Scheme.*

Figure 5: *Production of maize in Ahuazotepec Puebla under the "Program to increase the economic sustainability of the maize agroecosystem in Ahuazotepec, Puebla". Conventional Scheme.*

practices and what they entailed during a series of visits to the "Rancho Laguna Seca" experimental unit. However, they made the final decision as to if and which proposed practices they would use in their plots. Decision making in the TS was done collaboratively, with trained collaborators and producers discussing the alternatives and coming up with the best practice to be used.

Definition of Indicators: The selected indicators were yield and cost-benefit ratio. Grain yield (GY) was determined in t ha^{-1}, considering a 12% moisture content, was calculated as: GY = (FW x %DM x %G)/8800 [38], where FW = cob field weight in kg; %DM = dry matter percentage; %G = percentage of grain. Benefit-to-cost ratio (BCR) on the experimental plot was calculated as in Dominguez-Hernandez, et al. [29] using the average production costs per hectare ($6,300) and the value of the grain obtained in each cycle, considering a sale price of 4,900 MXN per t valid in Ahuazotepec during 2017.

Evaluated Indicators: Yield and Benefit to Cost Ratio: The program generated an improvement in the economic dimension of the maize agroecosystem for all the beneficiaries. Yield increases of between 50 and 3,500 kg per hectare were reported, with an average value of 1,323 kg ha^{-1}. The average yield was 2.7 t ha-1 with an average cost-benefit ratio of 2.12, that is, 1.12 pesos for each peso invested. Up to 73% of the beneficiaries had positive values in the BCR, which indicates that with the proposed management program they were able to increase the yield and recover the initial investment. Despite reporting increases in GY, at least 15% of the beneficiaries obtained yields of less than 1.2 t ha^{-1}, which even though lower than the average, is the amount necessary to cover the grain needs of a family unit for one year.

Considering the results of the program, and the two schemes of implementation, it was found that the Transdisciplinary Scheme increased an average of 1465.8 kg per hectare, while the increase in the group under the Conventional Scheme was 538.4 kg. This result may indicate that the design of programs where different actors of the system participate constantly during the production cycle generates greater benefits than those obtained with conventional schemes where only economic or in-kind assistance is granted.

When the program was designed, it was observed that there is a resistance to change rooted in the producers. This could be explained due to their previous experiences with government interventions in which they were left alone and there was no training or technical assistance to guarantee the results and the implementation of the proposed changes, which were often difficult to perform. Because of this, it was considered pertinent that the proposed modifications were small and relatively simple to carry out, in order to be accepted and subsequently replicated by the farmers after visiting the experimental unit. Also, the producers were continuously reassured there would be technical assistance available in case they needed it.

A high number of the producers who participated in the interventions expressed interest in making and sustaining the proposed changes to their systems, mainly because they observed increases in yield and lower production costs. However, the adoption and interest levels for both schemes were different. After the intervention, 100% of the participants in the TS adopted at least one of the proposed modifications, mainly manure fertilizers, higher planting density, split fertilization, and rational or reduced use of machinery and agrochemicals for cultivation, mulching, and soil amendments. In contrast, the CS only achieved 50% of long-term adoption of the improved practices once the government financial support was finished. This finding is similar to those of other intervention studies, where the integration of the community via a transdisciplinary approach, was key to ensuring adoption and continuity of the proposed solution as well as feedback on its performance, constant improvement and mutual learning [18, 50].

It has also been found that the success of agricultural interventions is also linked to the inclusion of education and training elements in their design (see Domínguez Hernández et al. in this special issue for a review [49]). More importantly, the collaboration element may have helped the beneficiaries to prevent disadoption of the proposed practices by providing continuous support, emotional and technical, needed to overcome possible limitations, strengthen community integration, and increase ownership of the program [51, 52]. In the present case, we attribute the higher rate of sustainable practice adoption to the collaboration and mutual learning aspects during the TS; since producers were able to learn the practices but also to freely adapt them and combine them with their own personal agricultural knowledge to address the specific biophysical conditions of their This could be explained due to their previous experiences with government interventions in which they were left alone and there was no training or technical assistance to guarantee the results and the implementation of the proposed changes, which were often difficult to perform. Because of this, it was considered pertinent that the proposed modifications were small and relatively simple, in order to be accepted and subsequently replicated. The producers who participated in the intervention expressed interest in making changes to their systems and to date have maintained the proposed changes, especially in fertilization practices. This finding is similar to those of other intervention studies, where the integration of the community via a transdisciplinary approach, was key to ensuring adoption and continuity of the proposed solution as well as feedback on its performance, constant improvement and mutual learning

[15, 50].

Follow-up visits were planned in 2020 to check if the changes were maintained by the community, however, due to the COVID-19 pandemic they were postponed until the spring-summer of 2021. During this visit, some of the beneficiaries stated that currently their production units are in transition toward complete agroecological management, and some have even fully adopted it. This was attributed to problems related to accessing agricultural inputs, particularly chemical fertilizers, first due to reduced availability and then increases in the cost, both of which have worsened in the last few years due to the pandemic and conflicts such as the Russo-Ukrainian war. Another aspect that could have contributed to this deeper agroecological change is the experience and knowledge sharing that could have occurred between participants from the TS and those from the CS one who had not yet adopted many agroecological measures. According to Altieri et al. [12], the ability to withstand external shocks such as this is a testament to the increased resilience of agroecology adopters. Additionally, the continuous and wider application of sustainable practices that reduce agrochemical use also reduces the possibility of future environmental problems that may compromise the health and livelihoods of the intervention beneficiaries [53].

4 Conclusions

The design of interventions for the improvement of agroecosystems requires a multidimensional, systemic, and transdisciplinary approach that not only makes possible the implementation of the proposals in real-world conditions but also improves the possibilities of success. As observed, interventions with a transdisciplinary approach had a greater impact on the community than those developed under the conventional scheme commonly used in support of Mexican agriculture. Additionally, it was observed that focusing on agricultural indicators of a multidimensional character such as measures for energy use efficiency, soil fertility, weed/pest incidence, and even some ecosystem services was required to address the challenges of local maize production. We hope that monitoring these indicators in the long term will help maintain natural resources and sustainability. Finally, cooperation between all actors was key to ensuring the success of the program and to helping in developing and implementing the solution. Government, academics, and producers can learn from each other in all stages, but in the latter case, we observed that participant involvement during the intervention was intensified, going from information providers, to consulting and finally to empowerment and ownership of the solution.

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Author contributions: MEDH had the idea for the research, adapted the methodology and conceived the experiments along with EDH. MEDH, ADH, EDH and GMB performed the experimental, laboratory and intervention parts of the project, and analyzed the results. EDH and MEDH drafted the manuscript and prepared the visual elements. MEDH, EDH, and RZB, all secured funding for the research. All authors critically revised and edited the text and results, and finally approved the manuscript.

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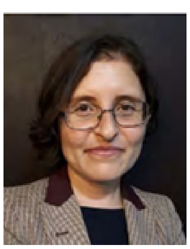

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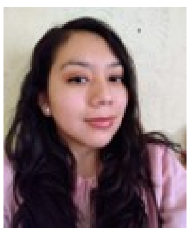

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