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Addressing Soil Degradation in Mexico Through Nitrogen-Fixing Agricultural Practices

The mountainous regions of Mexico have long been an important center in the history of maize domestication and the traditional milpa system of agriculture. For thousands of years, people in these regions have sustained food production through a variety of polycultural methods adapted to local ecological conditions. In recent decades, though, severe soil degradation has become a serious threat to the livelihoods of rural populations and to national food security. According to the National Forestry Commission of Mexico and the Secretariat of Environment and Natural Resources, an estimated 45% to 63% of soils in Mexico exhibit varying degrees of degradation resulting from erosion, deforestation, and unsustainable modern farming practices.

The economic and humanitarian effects of this ecological crisis are considerable. According to the Food and Agriculture Organization, soil degradation results in annual economic losses of up to $60 billion in Latin America (FAO, 2021). In Mexico, such losses affect rural smallholder farmers more than others, since they rely on rain-fed agriculture for both subsistence and income. As topsoil is lost and soil nutrients are depleted, agricultural land becomes increasingly incapable of supporting productive crop growth. This has raised a key research question: what is the effect of soil degradation on food security and crop yields in Mexico, and which biologically based interventions are most effective at reversing this damage?

To evaluate the extent and spread of this problem, one has to look at the farming populations most directly affected by soil degradation. The agricultural sector in Mexico is fundamentally based on production by small farmers, with about 73% of landowners cultivating five hectares or less (World Bank Group, 2019). A large part of this land is susceptible to climate variability, steep terrain, and rapid topsoil erosion, especially in the southern mountainous states such as Oaxaca and Chiapas, where rural poverty remains consistently high.

A good example is an Indigenous farming family in the Sierra Mixe area of Oaxaca. This type of family might practice subsistence farming on a three-hectare piece of land managed collectively within the traditional ejido system, a form of land tenure introduced after the revolution, under which the state grants land rights to a community that, as a whole, regulates the use of the land. The household's food system revolves around the milpa, an ancient intercropping system that involves growing maize (Zea mays), climbing beans (Phaseolus vulgaris), and squash (Cucurbita spp.) together to feed a family of six (Fonteyne et al., 2023). In a well-functioning milpa, the maize stalks support the climbing beans, the beans add nitrogen to the soil biologically, and the squash leaves provide ground cover that helps retain soil moisture and prevent weeds from growing. The family relies on this harvest for most of its calories and sells only the small surplus it produces in local markets to pay for essential needs such as healthcare and education.

Even though the milpa system has been passed down from one generation to the next, these households now face greater agronomic and socioeconomic pressure. Since their farmland is situated on steep slopes, heavy seasonal rainfall causes water-induced erosion that removes the nutrient-rich topsoil. At the same time, over many decades of pressure from the market and from policies has caused some communities to shift from diversified intercropping to chemical-intensive monoculture. Such practices frequently result in the soils losing their essential nutrients. Many smallholder families cannot afford to buy imported synthetic fertilizers, and when fertilizers are available, runoff can pollute the local water systems and pose additional public health risks. For them, soil degradation leads to lower harvests, seasonal malnutrition, labor migration, and a decline in both their economic situation and their cultural traditions.

The biophysical processes that lead to soil degradation in Mexico involve a rapid loss of organic matter and protective topsoil. In areas prone to it, such as Chiapas, soil erosion can amount to 274 tons per hectare per year (Copernicus Publications, 2018). The level of erosion is worsened by deforestation associated with timber production and by continuous cultivation on steep slopes without adequate terracing, ground cover, or other soil conservation practices.

Sheet erosion generally occurs when thin layers of topsoil are washed away by surface runoff, and rill erosion occurs when flowing water incises small channels in cultivated fields. The change from polyculture to monoculture has also reduced the biological functioning of the soil ecosystem. As a result, the use of synthetic fertilizers contributes to soil acidification, which is detrimental to native bacteria and mycorrhizal fungi. These organisms are important for soil aggregation, nutrient cycling, and the maintenance of long-term fertility.

The impact of this physical and chemical deterioration is directly linked to food security outcomes. Soils that have become degraded and compacted can hold less water and have lower levels of essential nutrients, especially nitrogen. Since nitrogen is required for the production of plant proteins, amino acids, and chlorophyll, nitrogen-deficient crops often exhibit stunted growth, chlorosis, increased susceptibility to pests, and reduced yields. In the Sierra Mixe area, a poor maize harvest can lead to serious nutrient deficiencies, particularly in carbohydrates and plant-based proteins, thereby perpetuating cycles of poverty that are hard to break.

A response that is feasible, sustainable, and culturally appropriate should involve the targeted cultivation of nitrogen-fixing Olotón maize, along with Canavalia leguminous cover crops and community-run seed banks. This integrated agroecological approach must be implemented locally in the Sierra Mixe and other high-altitude areas, not as a quick nationwide measure. Since it combats nutrient depletion and erosion through biological methods, the technique reduces the need for expensive synthetic fertilizers while reinforcing an agricultural system based on Indigenous farming knowledge.

The system functions via two complementary biological processes. On the one hand, Olotón maize, an Indigenous landrace originating in the Sierra Mixe area, develops special aerial roots that exude a mucilage rich in carbohydrates (University of California, Davis, 2018). This mucilage enables the development of a specific diazotrophic microbiome that fixes atmospheric nitrogen and thus meets about 29% to 82% of the plant's nitrogen needs, thereby reducing the need for chemical fertilizers (Van Deynze et al., 2018). On the other hand, Canavalia, commonly known as jack bean, can be grown between maize rows as a fast-growing cover crop. The root nodules of Canavalia contain Rhizobium bacteria that fix atmospheric nitrogen into ammonia available to plants, thereby improving soil fertility. Canavalia also forms a dense layer of vegetation that reduces the impact of raindrops, minimizes surface runoff, and helps prevent further loss of topsoil from sloped fields (The Nature Conservancy, 2022).

The implementation would require action coordinated by the local communities, the Mexican federal agencies, the research institutions, and the international development organizations. During the first six months, instead of giving priority to subsidies for costly and environmentally hazardous synthetic fertilizers, the Mexican Secretariat of Agriculture and Rural Development (SADER), together with the Food and Agriculture Organization (FAO) and the National Institute of Indigenous Peoples (INPI), would provide funding for municipal seed banks in the rural ejidos. These seed banks would be responsible for preserving, multiplying, and distributing locally adapted landrace seeds. From the sixth to the twelfth month, the agricultural extension programs would use the Campesino a Campesino, or Farmer-to-Farmer, method. In this method, trained local farmers would conduct field demonstrations on intercropping cycles, seed selection, erosion control, and cover crop management to ensure that Canavalia protects the soil without shading the young maize. From years one to three, the smallholder farmers who were taking part would test the Olotón-Canavalia system on pilot plots, while the regional agricultural universities

monitored soil nitrogen, erosion indicators, organic matter, and yields using low-cost soil testing kits. From years three to five, the seed bank operations would be extended throughout Oaxaca, Chiapas, and Guerrero only after the results of the pilot studies had confirmed both the agronomic and social feasibility. Participatory plant-breeding networks would then cross local maize varieties with Olotón traits to adapt nitrogen-fixing capacity to different microclimates. The funding could be obtained by redirecting a portion of existing federal subsidies for chemical fertilizers to seed bank infrastructure, farmer training, and transitional crop insurance, thereby ensuring that household income is protected during the adoption period.

The recommendation would affect various stakeholder groups in different but interconnected ways. Smallholder farming families would see their fertilizer expenses decrease, experience more stable crop yields, and benefit from better household nutrition. The indigenous ejido assemblies would retain control over seed stores and natural resources, thereby protecting the community's sovereignty and its right to make shared decisions. Federal agencies such as SADER and SEMARNAT could reduce their dependence on imported chemical inputs while making meaningful progress toward their soil restoration and rural development goals. Regional universities would have the opportunity to conduct applied, community-based agricultural research. International research organizations would collect field data on low-input, climate-resilient farming systems to help shape food security strategies for other mountainous agricultural areas.

Long-term success requires that institutional, ecological, and labor-related obstacles be addressed. To protect Indigenous communities from corporate biopiracy, seed bank activities should follow the Access and Benefit-Sharing rules set out in the Nagoya Protocol, ensuring that the Mixe communities retain their sovereign genetic rights over the Olotón landraces (Pskowski, 2019). To address photoperiod sensitivity at different altitudes, local seed banks should organize participatory breeding to incorporate Olotón characteristics into local maize varieties while keeping farmers in control of seed selection. The potential labor challenges associated with pruning and cover crop management can be reduced by conducting peer-to-peer training, especially by helping farmers time their intercropping cycles so that cover crops do not compete with maize for water when it is dry. Such precautions are necessary since an agroecological intervention cannot be considered sustainable if it leads to greater labor inequity, weakens Indigenous governance, or moves genetic resources away from the communities that developed them.

The expected effects would happen on both a short-term and a long-term basis. In the first one or two years, the establishment of Canavalia could lead to better ground cover, reduced surface runoff, greater biomass input, and reduced use of synthetic nitrogen fertilizers by households. These short-term advantages would be particularly important for subsistence households, which cannot afford to suffer sudden yield losses during the transition. After three to five years and beyond, ongoing biological nitrogen fixation, the accumulation of organic matter, and improved soil structure could help to establish more resilient rain-fed maize production. Thus, the intervention not only handles the immediate vulnerability of households but simultaneously supports the gradual restoration of degraded agricultural soils.

The recommendation does not call for the introduction of a completely new agricultural system but instead calls for improving and expanding existing Indigenous and agroecological practices. It is important to make this distinction because food-security projects are more likely to succeed when they are based on knowledge already recognized locally rather than replacing it with technologies imposed from outside. In other regions, similar agroecological methods — such as legume-based intercropping and farmer-managed seed systems among smallholder communities — have shown that soil restoration is most sustainable when farmers retain control over seed selection, field experimentation, and local adaptation. For Mexico, focusing on the Sierra Mixe and other highland areas offers a more practical approach than trying to address national soil degradation through a single centralized policy. Additionally,

other countries with similar climates and terrain may seek to benefit from the proposed solution, such as Guatemala, Honduras, and El Salvador.

To sum up, soil degradation presents a serious challenge to the agricultural stability, nutritional security, and cultural resilience of Mexico's smallholder farmers. Relying on chemical-intensive monoculture on steep slopes is not only environmentally unsound but also economically difficult for low-income rural families. An agroecological system based on the Olotón-Canavalia method, along with community-run seed banks, offers a practical and culturally appropriate solution. This approach helps improve biological nitrogen fixation, reduce erosion, and maintain Indigenous control over seed resources, so that Mexico can adopt a food-security strategy that is both scientifically sound and socially fair. Helping farmers by using self-fertilizing crops not only repairs degraded soil but also preserves agricultural independence, ensures rural economic security, and secures the long-term food supply for future generations.

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