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Review

Restoring Mexican Tropical Dry Forests: A National Review

Natalia Mesa-Sierra [1], Marinés de la Peña-Domene [1,2,*], Julio Campo [2] and Christian P. Giardina [3]

1 Centro Interdisciplinario para la Formación y Vinculación Social, Instituto Tecnológico y de Estudios Superiores de Occidente, Tlaquepaque 45604, Jalisco, Mexico; natalia.mesa@iteso.mx
2 Instituto de Ecología, Universidad Nacional Autónoma de México, Mexico City 04510, Mexico; jcampo@ecologia.unam.mx
3 USDA Forest Service, Institute of Pacific Islands Forestry, Hilo, HI 96720, USA; christian.p.giardina@usda.gov
* Correspondence: marinespd@iteso.mx

Abstract: Deforestation is the dominant threat to tropical dry forests (TDFs) in Mexico. Its causes include agriculture, tourism, and mining. In some cases, unassisted forest regeneration is sufficient to return diverse forest cover to a site, but in other cases, changes in land use are so severe that active restoration is required to reintroduce tree cover. The ecological and social constraints on TDF restoration in Mexico are poorly understood. To address this knowledge gap, we synthesized relevant restoration literature for Mexico published between January 1990 and February 2020. We examined 43 unique articles about TDF restoration practices in Mexico to identify (1) the national distribution of TDF restoration projects, (2) restoration objectives, and (3) factors contributing to TDF restoration success or failure. The largest number of restoration sites were in the Yucatan Peninsula, and the most common objective was to restore dry forest vegetation on lands that had been used for agriculture or impacted by fires. Planting seedlings was the most widely reported restoration strategy, and plant survival was the most frequently monitored response variable. Maximum annual temperature and the Lang Aridity Index were the best predictors of plant survival, which ranged from 15% to 78%. This synthesis highlights how national restoration inventories can facilitate the development of a restoration evaluation framework to increase the efficacy of restoration investments.

Keywords: tropical dry forest; ecological restoration; restoration drivers

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1. Introduction

The tropical dry forest (TDF) biome represents over 30% of all forest types in the tropics, is of high societal importance, and is among the most impacted by human land use [1]. Nearly 90% of the Earth's TDF have been heavily altered by agriculture or ranching. The extent of these land cover changes makes TDF one of the Earth's most threatened terrestrial ecosystems [2]. Furthermore, the practices associated with these land cover transitions typically impact soil fertility [3,4], ecosystem hydrology [5,6], and ecology [7,8], creating conditions that constrain natural regeneration. For example, the management of repeated fires to maintain pastures depletes soil seed banks, kills sprouting woody vegetation, and increases nutrient loss by soil erosion. In recent decades, restoration actions and unassisted forest regeneration have been applied globally with the goal of accelerating the return of forest cover to degraded TDF landscapes [9,10], but synthetic assessments of the drivers of restoration success or failure in TDF have been lacking.

Here, we examine the restoration of Mexican TDF. TDF is distributed in 12 of the country's 53 ecoregions (a geographically defined area that encompasses distinct ecological characteristics and assemblages of natural communities [11]). Most of the country's TDFs are in the Pacific Basin, the Yucatan Peninsula, and central Mexico [11–14]. In Mexico, TDFs support high levels of biological diversity despite having a history of sustaining human communities that spans from pre-Hispanic times to the present. For example, the Mayas of the Yucatan Peninsula and the Totonacas of Veracruz established thriving societies for over two millennia in Mexico's TDF [15–17], in part by relying on slash-and-burn agricultural management. This close association with human communities has resulted in landscapes dominated by a mosaic of secondary TDFs in different stages of succession [7,18]. TDF has high ecological and cultural value; thus, to be effective, conservation planning and management must integrate diverse socio-ecological elements.

The extensive biological and cultural diversity of Mexican TDFs is closely related to the wide variation in their climatic, topographic and edaphic properties [19]. Precipitation amounts vary twofold, with TDFs in El Bajio (central Mexico) receiving mean annual precipitation (MAP) of 600 mm, TDF landscapes in the Pacific Basin and Yucatan Peninsula receiving MAP values of 600 to 1000 mm, and the TDFs of Veracruz receiving >1000 mm MAP. In terms of topography, TDFs are found in Mexico's plains regions, which are concentrated on the Yucatan Peninsula, as well as in mountainous systems typical of Morelos and Veracruz. TDFs are found as low as sea level and are most common around 900 m a.s.l but can occur up to 2020 m a.s.l. [14,20]. As a result, Mexico's TDFs strongly vary with respect to plant biodiversity [12,14] and have wide regional variation in biogeochemical processes [3].

Only 10% of the TDF biome in Mexico is under some scheme of protection [21]. As a result, 70% of its pre-Hispanic extent has been converted to other non-forest cover types [21]. Approximately 62% of the remaining forests are modified or disturbed [12]. The main threat to Mexican TDF is deforestation associated with livestock production and agriculture but also tourism-focused development and mining [15,22]. The degradation and loss of TDF impact local communities' well-being and access to quality water and food. Degradation and deforestation exacerbate the effects of climate change and reduce socio-ecological resilience [23,24]. The consequences of TDF degradation include degradation of soil fertility; desertification; magnification of the effects of natural disturbances (e.g., landslides, hurricanes); intensification of drought effects due to reduced water holding capacity [22,25]. Communities, non-governmental organizations, academic institutions, and state and federal agencies have all identified TDF as a habitat for unique biodiversity and an important source of fiber, fuel, and ecosystem services in Mexico. Given the growing need for TDF conservation and where possible restoration in Mexico, there is a growing need to synthesize the options for and outcomes of unassisted forest regeneration and active restoration in TDFs [18].

Unassisted forest regeneration relies on the alleviation of threats, for example, by fencing, to exclude grazing animals and thus protect growing vegetation. This initial step in unassisted forest regeneration supports successional processes that lead to forest recovery—even in sites that have been severely degraded. The severity of degradation is often a function of the extent to which the avenues of regeneration (i.e., advanced regeneration, root and stump sprouts, seed bank, and seed rain) have been reduced or eliminated at a site. In unassisted forest regeneration, recovery rates can be slow and successional trajectories uncertain if seed sources are limited or far from the site, [16,26]. Conversely, if all of the avenues of regeneration are present on a site, or if a more degraded site has sources of diverse and desirable seeds nearby (e.g., intact forest) with a healthy community of seed-dispersing species (e.g., birds, bats), recovery will proceed more quickly [27]. In such cases, degradation of soils could become more limiting to regeneration than seed availability [25]. In such cases, degradation of soils could become more limiting to regeneration than seed availability.

In some cases, where land use has been intense or has been practiced over the medium or long term, the time frame for unassisted forest regeneration may be too slow from the perspective of the manager or landowner. Alternatively, sites may be dominated by highly competitive undesirable species that represent a barrier to recruitment by desirable species. For example, African savanna grasses produce forage for livestock but compete strongly for resources and thus exclude native woody recruitment [16,28–30]. For both of these cases, active restoration would need to be implemented including soil amelioration, cover-cropping, tree planting, weed control, and construction of artificial roosts to attract seed dispersers. There is a continuum from unassisted forest regeneration to active restoration, which spans from minor disturbance abatement to intensive plantation silviculture. The scale of restoration investment at a site, therefore, depends on a balance of desired outcomes, assessed conditions, resource availability, and the likelihood of a successful outcome [31]. While this set of factors can be quite variable across TDF sites, understanding differences and commonalities is a necessary step for guiding future efforts from local to regional, and even national, scales.

Mexico is aligned with several restoration-relevant international commitments and initiatives, including the International Union for the Conservation of Nature's Bonn Challenge, which seeks to bring "150 million ha of degraded and deforested landscapes into restoration by 2020, and 350 million hectares by 2030"; the complementary United Nations' New York Declaration on Forests, which seeks to support Bonn Challenge goals while "halting deforestation, improving governance, increasing forest finance, and reducing emissions from deforestation and forest degradation as part of the Paris Agreement"; and regional efforts such as Initiative 20 × 20, which is designed to guide implementation of the Challenge and Declaration goals in Latin America and the Caribbean. In engaging these efforts, Mexico has set the target of restoring 8 million ha of degraded land across ecosystem types. Efforts to develop strategies for planning this recovery have been variable and highlight the need to develop a science-based and indicator-driven planning process that identifies barriers to and drivers of success.

To these ends, the Mexican government has begun to identify priority areas for restoration, with restoration research serving to identify and evaluate the most efficient restoration strategies for a range of sites [16,31]. There is currently no inventory or comprehensive assessment of restoration strategies across Mexico. This potentially compromises the efficiency and collective impact of restoration investments into meeting local to national goals. The main objective of this study is to compile and analyze published restoration strategies that have been applied in Mexico to enhance TDF biodiversity, ecosystem services, and human well-being goals. Specifically, we ask: (1) What is the distribution of TDF restoration projects across Mexico? (2) What have the main restoration objectives been in Mexican TDF restoration projects? (3) Which factors have contributed to successes and failures in TDF restoration? To address these three core questions, we used a literature search to identify the main advances and gaps in knowledge of TDF restoration in Mexico, including site characteristics that facilitate selection for restoration and the main drivers of restoration success. In so doing, this study provides a baseline of information to optimize investment in TDF restoration in Mexico.

2. Materials and Methods

2.1. Study Regions

Mexico has one of the largest areas of seasonally dry vegetation in the Neotropics [32], which occurs across 12 TDF ecoregions (Bajio Dry Forest, Balsas Dry Forest, Central American Dry Forest, Chiapas Depression Dry Forest, Islas Revillagigedo Dry Forests, Jalisco Dry Forest, Sierra de La Laguna Dry Forest, Sinaloan Dry Forest, Sonoran-Sinaloan Transition Subtropical Dry Forest, Southern Pacific Dry Forest, Veracruz Dry Forest, and Yucatan Dry Forest). These 12 ecoregions are found primarily on the Pacific coast, including the Balsas Basin; in the northwestern portion of the Yucatan Peninsula; in central Mexico; on the Gulf of Mexico [12,33]. These four geographic areas differ (Table S1) with respect to climatic, topographic, and edaphic conditions; floristic composition; plant community structure and dynamics; ecosystem function [12,13]. An extended dry season is the primary determinant of TDF globally, and in Mexico, TDF is characterized by a mean dry season of just over 7 months, with dry season months receiving < 100 mm of rainfall [34]. There is high variability in precipitation amounts and distributions across Mexico's TDFs, with the wettest receiving 1370 mm of MAP in a 7-month rainy season and the driest receiving 450 mm of MAP in a 3-month rainy season. Pacific coast TDF occurs from 0 to 500 m a.s.l., supports a highly diverse and largely endemic flora composed of 651 identified vascular plant species, but which has been strongly impacted by agricultural land clearing, tourism-based development, and hurricanes [12,35]. TDF of the Yucatan Peninsula's karst plain occurs from 0 to 190 m a.s.l., supports more than 200 woody species, and is characterized by a high density of pre-Hispanic Maya settlements, indicating a long-term human footprint on TDF diversity [36,37]. The central region TDF is characterized by an elevation of approximately 1000 m a.s.l., more than 900 species of vascular plants [38], and contemporary intensive agriculture that has expanded rapidly in the past 40 years. TDF of the Gulf of Mexico occurs across rolling hills and supports diverse deciduous forest species with a species composition that also includes tropical dry oak forest [39]. Overall, Trejo and Dirzo [14] highlight that the wide variety of conditions in which the TDF biome is distributed in Mexico gives this forest type high floristic diversity that includes 917 tree species in 368 genera representing 76 families.

2.2. Protocol for Literature Review

We conducted a literature search using the Web of Science (WoS) and Google Scholar databases for studies published between January 1990 and February 2020. Titles, abstracts, and keywords were queried for the following terms in WoS: ("Seasonally Dry Tropical Forest*" OR "Dryland*" OR "Tropical Dry Forest*") AND ("Restoration*" OR "Reforestation*"). Since Google Scholar is not as strongly systematized as WoS, we performed the following six separate searches: ("Seasonally Dry Tropical Forest" AND "Restoration"), ("Seasonally Dry Tropical Forest" AND "Reforestation"), ("Tropical Dry Forest" AND "Restoration"), ("Tropical Dry Forest" AND "Reforestation"), ("Dryland" AND "Restoration"), ("Dryland" AND "Reforestation"). We selected articles with the sections mentioned above in English, based on the search terms. There were some articles included in the review that had an abstract in English, but the main text was in Spanish or Portuguese. The WoS and Google Scholar searches yielded 2893 unique studies (Figure 1). We then performed a preliminary review and filtering of identified papers to include only articles that (1) evaluated the results of active restoration in TDF, (2) described empirical studies whose explicit objective was to restore TDF ecosystems by active planting (research on implementation) or testing management methods (experimental research), or (3) studies that were developed specifically in Mexico. Our search ultimately yielded 43 published studies that met one of these three criteria (Figure 1). We acknowledge that in Mexico, there are many important restoration efforts, including a wide diversity of efforts carried out by communities or are promoted by non-governmental organizations. However, since many of these efforts are implemented without accompanying research, they did not meet our criteria and were, therefore, not included in this review. Their exclusion from this study in no way suggests that they are of lesser ecological value or that such efforts should receive less support.

2.3. Characterization of the TDF Ecoregions in Mexico

From each of the 43 reviewed studies, we extracted geographic coordinate information to generate shapefiles that were used to obtain data on spatial variables to (1) describe each restoration site, (2) understand relationships between spatial variables and success attributes of the restored site, and (3) compare the success of restoration across TDF restoration sites. Data for the climatic variables and the MODIS-based Normalized Difference Vegetation Index (NDVI) were obtained from different repositories including NASA Earth Observation (NEO, https://neo.sci.gsfc.nasa.gov/, accessed on 1 February 2020); Climatic Hazards Center at University of California Santa Barbara (www.chc.ucsb.edu/about, accessed on 1 February 2020); Numerical Terradynamic Simulation Group (NTSG) at the University of Montana (www.ntsg.umt.edu/, accessed on 1 February 2020); Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC); Mexico's National Commission for the Knowledge and Use of Biodiversity (CONABIO) GeoInformation Portal (www.conabio.gob.mx/informacion/gis/, accessed on 1 February 2021). The data layers contain information from the time intervals between the years 2000 and 2020 when satellite information was available. We extracted these to calculate mean maximum annual air temperature (°C), mean minimum annual temperature (°C), mean annual precipitation (mm $year^{-1}$), mean annual evapotranspiration (mm $year^{-1}$), mean annual Normalized Difference Vegetation Index (NDVI), and Lang Aridity Index [40]. This last index is characterized by estimating a precipitation factor, given by the relationship between mean annual precipitation and temperature as follows:

$$I_L = \frac{P}{T}$$

where P is the annual precipitation (mm), and T is the annual temperature (°C). This index has five classes, depending on its value, varying from arid (<20) to per-humid (>100) [40]. For each of the restoration sites, soil taxonomy information was used to assign low, medium, or high fertility classes. We obtained the information on the soil classification from the studies and, for cases in which it was not specified, we extracted the data from the shapefile of soil types at the national level of Mexico's National Institute of Statistics and Geography (INEGI) [41]. Finally, a database was generated for each study, with its soil taxonomy and its fertility category (Table S2).

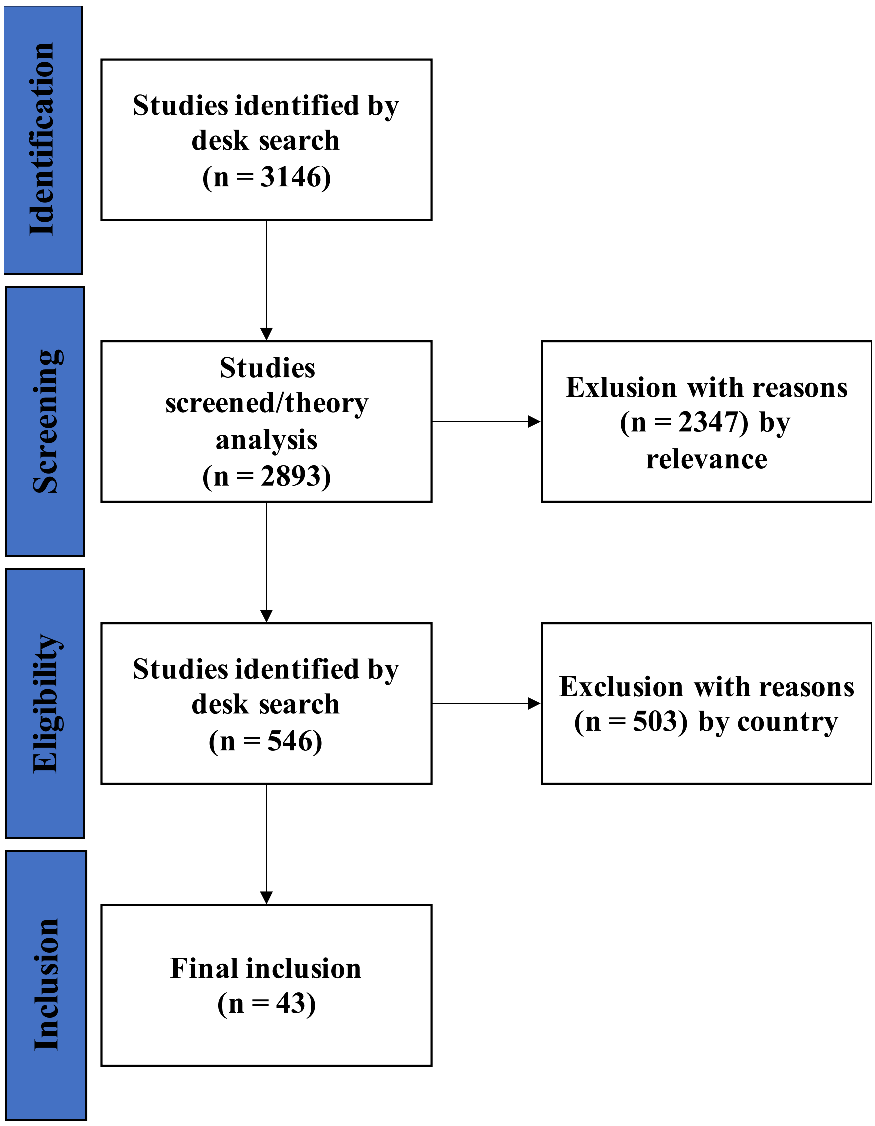

Figure 1. Review method diagram.

To better frame restoration sites with respect to the Mexican Government's national assessment of ecological degradation and restoration urgency, we used geospatial raster data from CONABIO to integrate restoration priority, an Anthropic Impact Index, an Ecological Degradation Index, and projected Climate Stability Index, for the 2015–2039 period. For restoration priority, CONABIO's prioritization for restoration corresponds to biological importance including conservation priorities and priority vegetation, as well as the feasibility of restoration based on degradation level, land use, fragmentation, and elevation. From these raster data, CONABIO has assigned high, medium, and low priority to restoration areas across Mexico. The Anthropic Impact Index integrates land use, fragmentation, climate change, and nitrogen deposition from the atmosphere, and scales positively with human impact. The Ecological Degradation Index reflects the intensity of the loss of vegetation cover in the last 25 years. The Climate Stability Index summarizes dynamically downscaled data from global circulation models for Mexico, including CNRMC-M5, GFDL-CM3, HADGEM2-ES, and MPI-ESM-LR based simulations for the RCP 8.5 scenario proposed by the IPCC [42].

2.4. Map of the Restoration Locations

We used GIS to visualize all restoration sites with additional layers including distribution of the twelve TDF ecoregions in Mexico and the various data layers extracted from the CONABIO repository [42]. Geospatial analyses then allowed us to address our three core questions and evaluate the Mexican government's prioritizations.

2.5. Data Analysis

From the restoration studies, we analyzed five main attributes: type of study, number of publications over time, site characteristics, restoration methods, and success metrics. The type of study was classified as either experimental research or implementation research where experimental studies evaluate the efficacy of restoration treatments while implementation research documents the results of restoration programs. Likewise, we used the publication date of the studies to analyze trends in the annual number of studies between January 1990 and January 2020, and how objectives of restoration studies have changed over time. We examined the causes of degradation or land use prior to the application of restoration methods and assessed which approaches have been most frequently used across Mexico. We also classified restoration objectives according to what the authors specified as the aim of the study into three broad categories: (1) those that aim to recover vegetation structure and composition including representation of targeted species, canopy cover, canopy height, density; (2) those focused on functional recovery of ecosystem processes including productivity, nutrient cycling, or biological interactions; (3) those that aimed to recover social benefits, including improving ecosystem services provisioning, or recovery of species with cultural or economic value. Additionally, we evaluated the metrics used to monitor the progress of restoration projects and delineated seven categories (see Table S3 for details): (1) vegetation structure, (2) functional attributes of the vegetation, (3) ecosystem functions, (4) soil, (5) biotic interactions, (6) biotic composition and diversity, and (7) services and social outcomes.

The survival percentage of planted seedlings was by far the most utilized metric, so we used this metric to assess restoration success across study sites. We only included studies that relied on reference sites (as defined by [43]) or control sites, for example, nearby preserved sites or similar sites not receiving treatment. These were then used to evaluate how survival correlated with climatic, edaphic, and topographic variables, restoration priority, Anthropic Impact Index, or Ecological Degradation Index (as defined by [42]).

For all analyses, we used ordinary least squares (OLS) regressions. To meet OLS regressions assumptions, we tested for normality. In the case of soil fertility, we used generalized linear models (GLMs) with a Poisson error type to evaluate its relationship with survival. When we obtained significant differences, we conducted a post hoc contrast test

(Tukey) to determine differences among categories. All statistical analyses were performed in R software [44].

3. Results

3.1. Overview of Restoration Studies in Mexico

The searches yielded 43 unique articles that met our review criteria. The majority (61%) were studies focused on field restoration, while 16% combined field and greenhouse work. The remaining 23% were entirely greenhouse-based or synthesis papers (Figure 2). Approximately 68% of the reviewed studies were experimental and designed to better understand restoration processes with the larger goal of increasing the probability of restoration success or the implementation of a new methodology. Overall, 20% of studies described research on implementation projects, and 10% were syntheses that focused on included TDF restoration in Mexico.

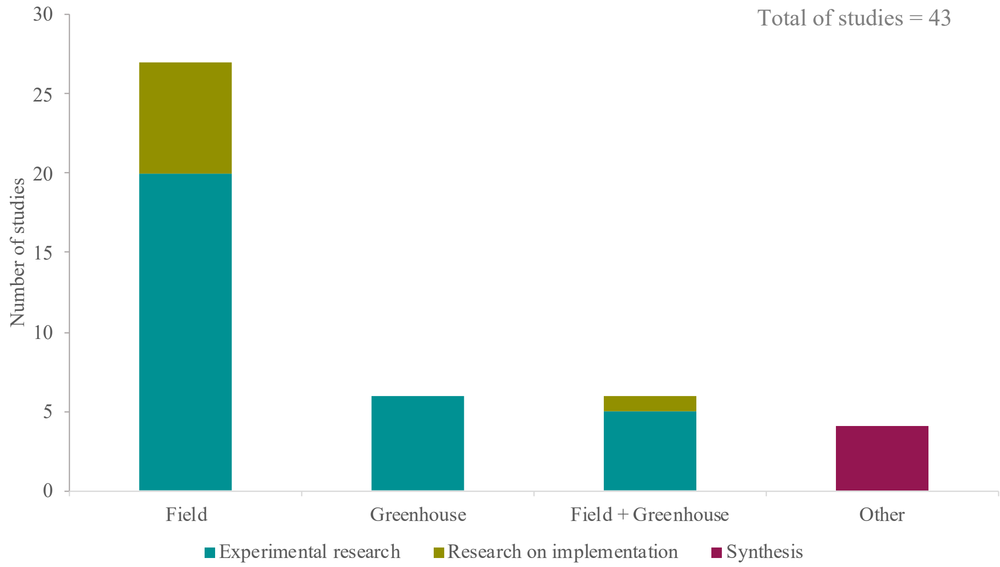

Figure 2. Distribution of restoration study types addressing Mexican TDF, including field studies, greenhouse studies, studies using a combination of field and greenhouse approaches, or synthesis studies that focused on or included Mexican TDF. Experimental research: studies that tested management methods. Implementation research: empirical studies whose explicit objective was to describe restoration of TDF ecosystems by active planting. Synthesis research: reviews that compared examined results from multiple studies.

In the 30-year study period evaluated with our search parameters, studies for the Mexican TDF biome appeared between 2003 and 2019. The main objective of most restoration studies was the recovery of vegetation structure or both vegetation structure and function (Figure 3). The years between 2010 and 2015 saw the highest number and most diverse studies evaluated in this analysis, with studies also including the full diversity of goals. Overall, however, there were few studies that included social/human well-being goals, with socially focused studies published only in two years (2011 and 2012).

The most common management activities preceding restoration at the sites examined here were cattle ranching, agriculture, and anthropogenic fire (89% of the total; Figure 4a). Many sites reported mixed previous land uses. For example, across the TDF biome, crops can be planted immediately after land clearing when there is a fire-related peak in soil fertility. Then, as nutrient supply declines over time, crops give way to forage grass species for cattle grazing, with pastures being managed with periodic fire to reduce recruitment of woody species. There are other isolated types of uses that we identified for the country (see details in Table S4). The longest time of previous land use reported in the reviewed studies was between 46 and 50 years (3% of the total, data not shown). At least one site reported continued land use during restoration.

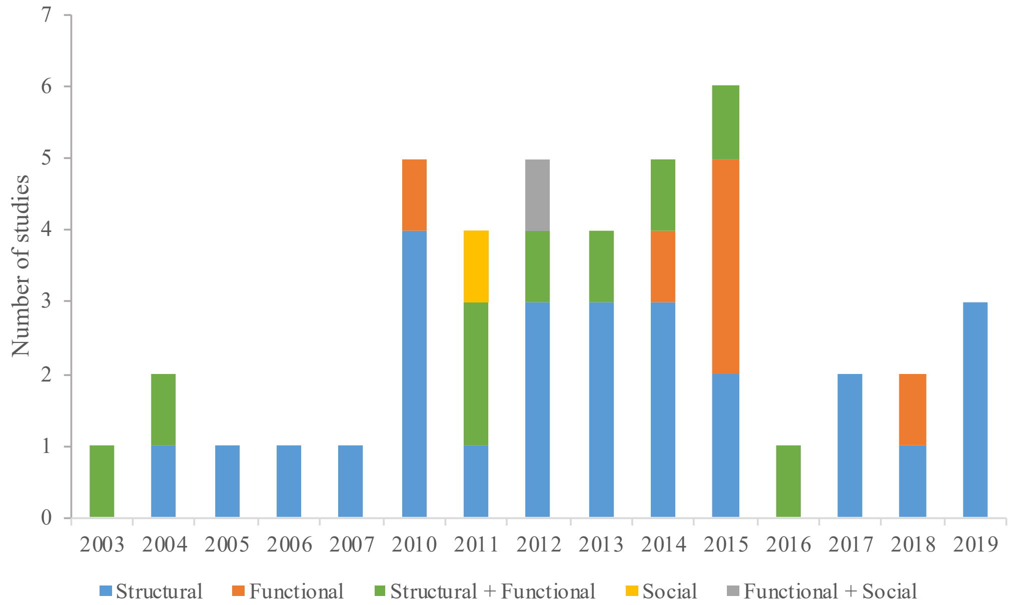

Figure 3. Number of studies published between 2003 and 2019 in Mexican TDF sites. The main objective of the studies is specified with different colors. We classified these objectives according to the main aims of the studies as structural (when methods were focused on recovering the vegetation structure and/or composition), functional (when the study included actions focused on recovering ecosystem functions), and social (when the studies included improving the impact of the ecosystem on human well-being). Some studies presented more than one goal (e.g., structural + functional or functional + social).

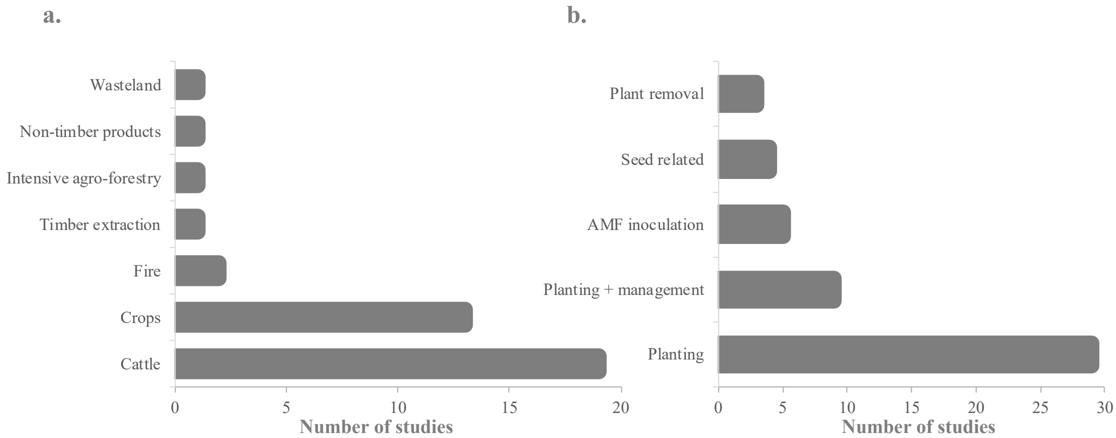

Figure 4. Previous management (**a**) and restoration strategies (**b**) reported by the reviewed studies examining restoration practices and success in the TDF biome of Mexico. The categories of restoration strategies correspond to planting, which refers to the strategy of sowing of seedlings or juveniles; planting + management, which includes those additional strategies to plantings such as animal exclosures, fertilization, irrigation, shade, mulches, and hydrogel; arbuscular mycorrhiza fungi (AMF) inoculation; seed related refers to direct seeding of a site with seeds of desirable species; plant removal includes strategies for the removal of unwanted plants, for example, via weed control, herbicide applications and physical grass removal.

The most commonly used restoration strategy was direct planting with desirable species, followed by plantings that included additional practices to enhance success efforts, such as fertilization and watering (Figure 4b, see details on Table S3). The least used strategies reported in reviewed studies corresponded to plant removals or plant control (Figure 4b, see details on Table S4). The length of the monitoring period ranged from 30 days to 10 years, with an average of 1 year (Figure S1). For direct planting or seeding studies, an average of 10 species were used (range = 1 to 39 species).

The genus with the highest number of reported utilized species was *Bursera* (*B. copallifera*, *B. glabrifolia*, *B. linanoe*, and *B. simaruba*), which have early successional properties including tolerance to harsher conditions. The five most frequently used species in the reviewed studies were *Guazuma ulmifolia* (in five studies), *Brosimum alicastrum* (in four studies), *Ipomoea wolcottiana* (in four studies), *Leucaena leucocephala* (in four studies), and *Cedrela odorata* (in three studies).

For studies including field experiments, the total restored area was 1143 ha, which is about 0.003% of the total estimated TDF area for Mexico. Most studies reported restored areas between 1 and 5 ha (59%; Figure 5), highlighting the fact that most studies are experimental. The Comisión Nacional Forestal (CONAFOR, the government agency responsible for forest management) has contributed with the restoration of 0.07% of the estimated original extent of TDF, with most restoration in Mexico being led by governmental initiatives [45].

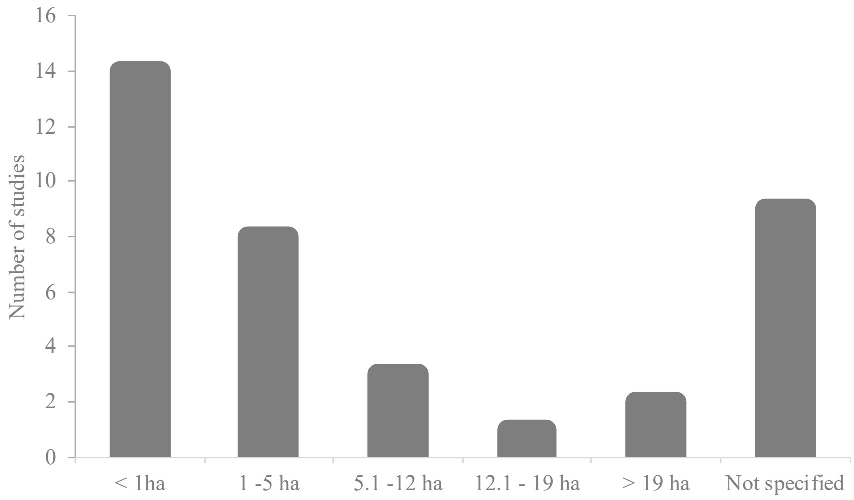

Figure 5. Number of studies in Mexican TDF sites reported for the different area categories. Not specified corresponds to studies not reporting the area being examined.

3.2. Under Which Conditions Does Restoration Occur in Mexico?

The Yucatan Peninsula supported the largest number of studies (eight studies), followed by central Mexico, the Gulf of Mexico, and the Pacific Basin. However, it is necessary to highlight that there are sites that are of particular interest and had a high number of studies, such as the site located in Chamela (Pacific Basin). The Yucatan sites occurred mostly in areas of high priority for restoration, high anthropic impacts, and projected low climate stability between 2015 and 2039 (Figure 6). In contrast, most restoration sites in the Pacific Basin and central zone regions were located in low restoration priority and low Anthropic Impact Index zones. Furthermore, the Pacific Basin was characterized by low a Climatic Stability Index. In the Gulf of Mexico region, restoration study sites were located in medium priority restoration areas with medium values for Anthropic Impact Index and Climate Stability Index. Despite the vulnerability of the northernmost distribution of TDF in Mexico, revealed in areas with high Anthropic Impact Index values and low Climatic Stability Index, this region supported the lowest number of the reviewed studies (Figure 6c,d). Additionally, most of this region is not considered as having a high restoration priority.

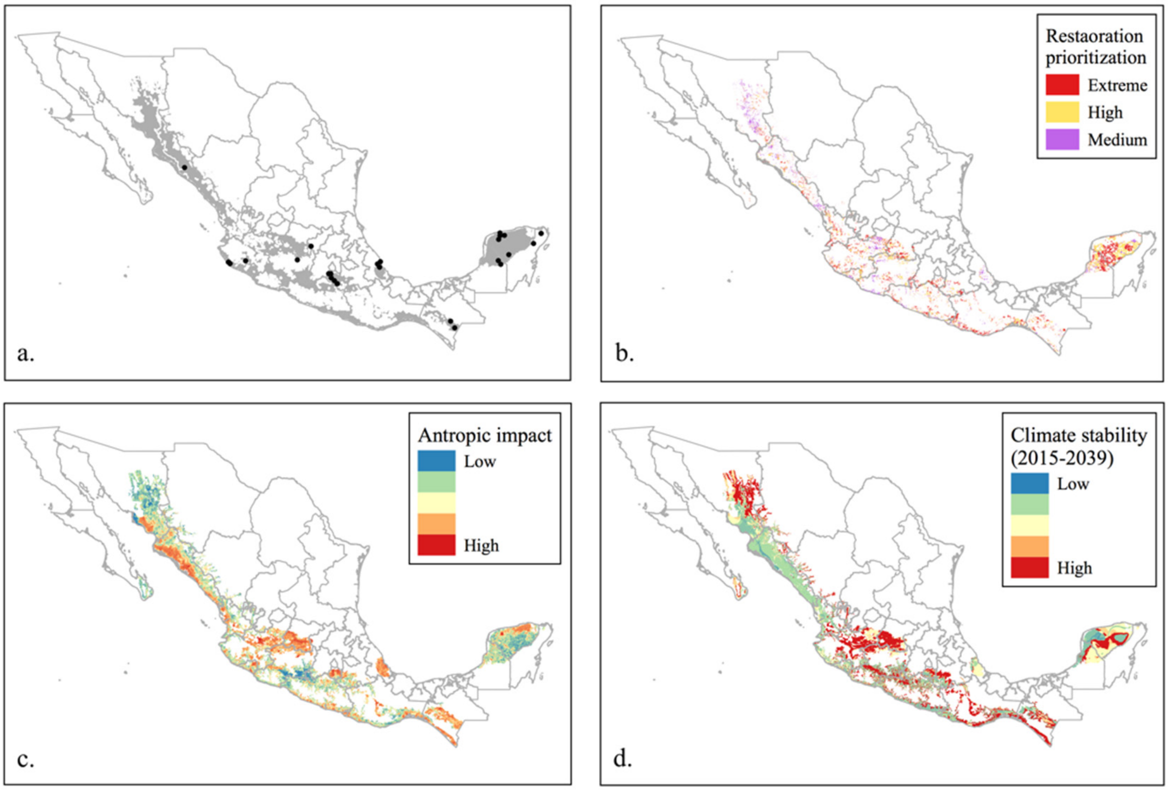

Figure 6. Distribution in Mexico of (**a**) the tropical dry forest ecoregions (grey) and the sites reported in the reviewed studies (black dots), (**b**) the zones that have been prioritized for restoration [37], (**c**) the anthropic impact index [37], and (**d**) the projections of climate stability for 2015–2039 period [37]. See the Methods Section for the details of each of the indices.

Most TDF restoration studies in Mexico are conducted at sites with total annual precipitation <1500 mm, mean annual temperature >30 °C, minimum annual temperature >24 °C, maximum annual temperature >37 °C, and potential evapotranspiration >480 mm year^{-1} (Figure 7a–c). In the case of the Lang Aridity Index, most TDF restoration studies in Mexico were carried out in semi-arid sites (Figure 7f).

Studies were relatively evenly distributed across NDVI and soil fertility values (Figure 8a,b), with most studies falling between NDVI values of 0.021 and 0.034. We observed that studies were located in regions characterized by low and high Anthropic Impact Index in the same proportion, and mostly with high Ecological Degradation Index (Figure 8c,d).

3.3. Response Variables

A total of 22 response variables were identified across all of the studies (Figure 9). Vegetation structure metrics were the most reported in our set of reviewed studies (52%), while services and social outcomes were the least reported (2%). Plant survival was the most common metric of direct planting performance (33%), followed by germination of seeds (12%) and then height growth (9%) (Table S3).

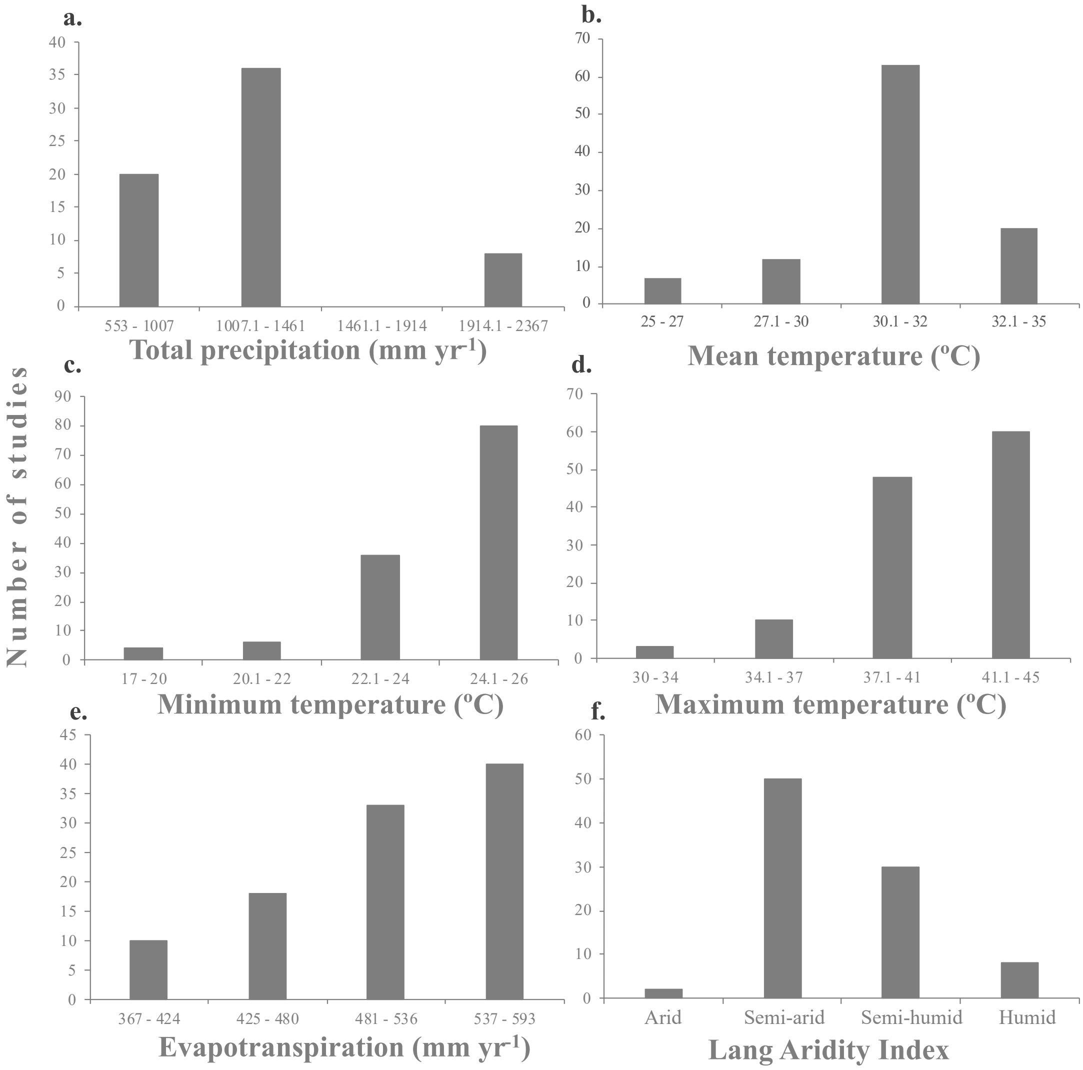

Figure 7. Frequency of reviewed Mexican restoration studies in the different categories of climatic variables: (**a**) total annual precipitation (mm yr^{-1}), (**b**) mean annual temperature (°C), (**c**) mean minimum annual temperature (°C), (**d**) mean maximum annual temperature (°C), (**e**) mean annual potential evapotranspiration (mm yr^{-1}), and (**f**) Lang Aridity Index.

A total of 12 studies (28%) reported planted seedling survival as a response variable and used this metric to monitor the progress of their restoration strategies. Of these, six included either a preserved area or control plots as a reference site. Across these 6 studies, planted seedling survival ranged from 78% to 15%, while in adjacent preserved forest, survivorship ranged between 49% and 79%, and for control plots, from 5% to 67%. The restored and reference sites had similar values for and variation about the survival variable and did not find significant differences among the survival rates of the three compared categories (Figure 10). Exclosures, fertilization, and shading were the most common practices used to improve planting success (Table S4).

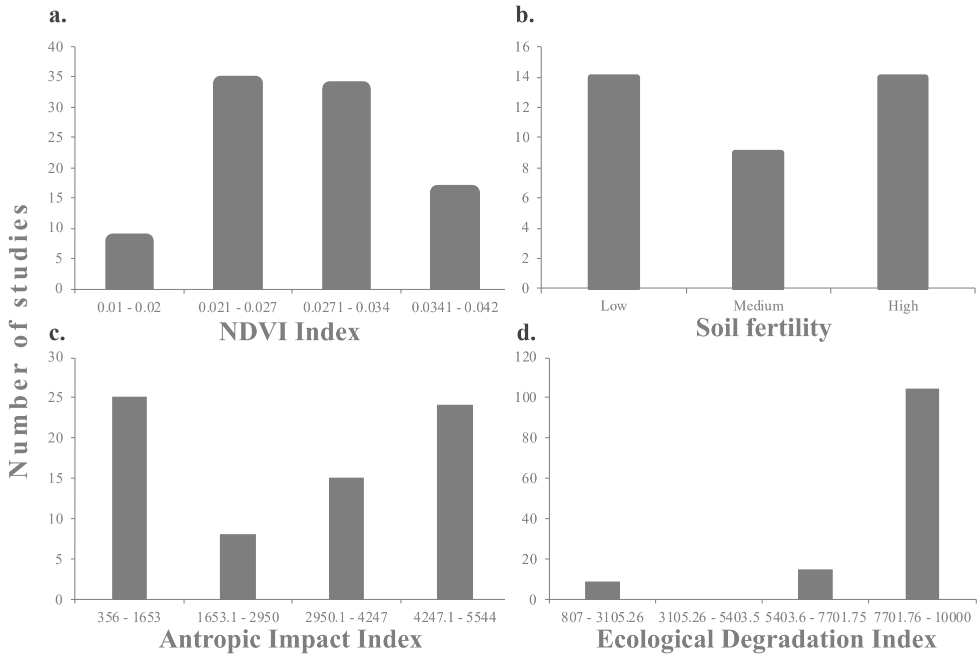

Figure 8. Frequency of studies in Mexican TDF as a function of (**a**) mean Normalized Difference Vegetation (NDVI) Index, (**b**) soil fertility, (**c**) Anthropic Impact Index [37], and (**d**) Ecological Degradation Index [37].

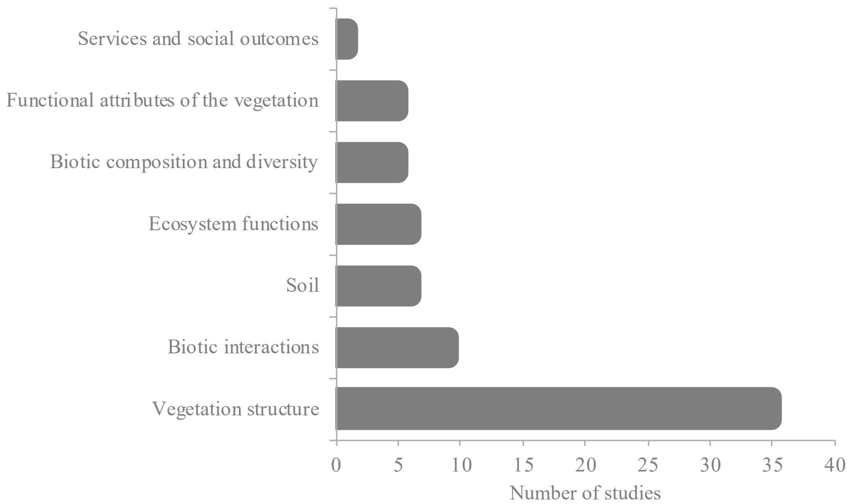

Figure 9. Metrics used in the restoration studies of Mexico TDF. Seven categories were defined (see Table S3 for details): vegetation structure, functional attributes of the vegetation, ecosystem functions, soil, biotic interactions, biotic composition and diversity, and services and social outcomes.

3.4. Drivers of Restoration Success

The success of restoration strategies expressed as plant survival increased significantly as maximum annual temperature declined, and as the Lang Aridity Index and soil fertility increased. Success was marginally affected (p = 0.10) by mean total annual precipitation and the mean annual air temperature (Figure 11). In contrast, plant survival was not sensitive to variation in elevation, Anthropic Impact Index, or Ecological Degradation Index (Figure S2).

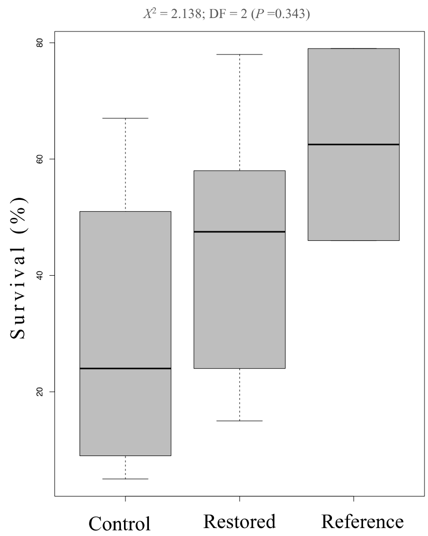

Figure 10. Percentage survival reported by the reviewed studies in restoration plots in Mexican TDF, and adjacent control plots not receiving a restoration treatment or in reference plots, for example, within preserves.

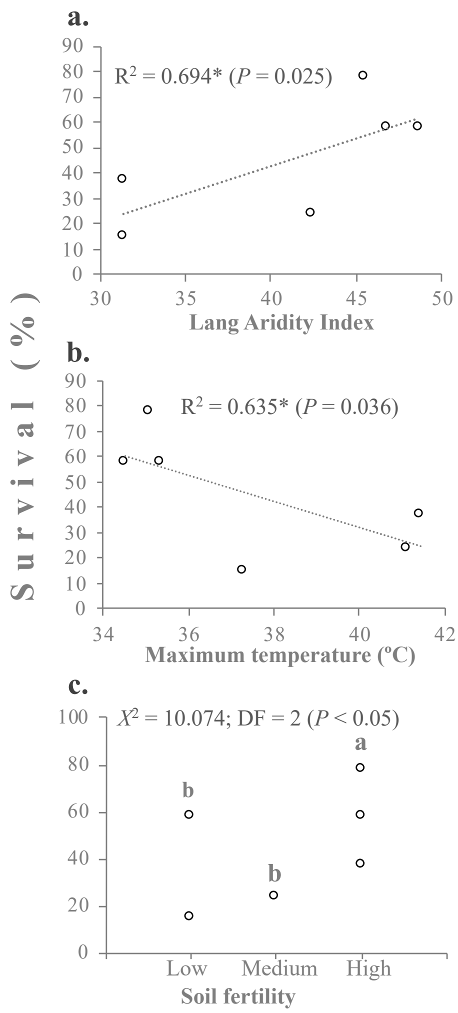

Figure 11. Relationships between plant survival reported in restoration studies in Mexican TDF and environment variables: (**a**) Lang Aridity Index [36], (**b**) mean maximum annual temperature (°C), and (**c**) soil fertility. For the case of soil fertility, for which a GLM was performed (see Methods), different letters show significant differences between forest types (Tukey test; $p < 0.05$).

4. Discussion

Most of the reviewed restoration efforts in Mexico corresponded to experimental projects in small areas (less than 5 ha). These projects are mainly located in regions close to research centers, higher education centers, or in rural properties that belong to educational institutions, as is the case of the Biosphere Reserve Chamela-Cuixmala. This is consistent with previous research that shows that restoration efforts in Mexico come largely from academic institutions [45,46], mainly through resources from the federal government. As with other TDF regions, the majority of studies examined here were carried out in protected areas and on small scales [9,47], which many times respond to security issues in the territories. Nevertheless, there are other extensive but informal restoration efforts in Mexico that are unpublished or did not meet our search criteria. The most commonly reported restoration strategy in our study set is direct planting, which typically included a complex set of practices: identification of ecologically, economically, or culturally valued species; seed collections from disease-free individuals with desirable traits; propagation that yields healthy seedlings; careful direct planting techniques and micro-site selection to yield the highest rates of plant survival, supplemental watering, or fertilization [16,48–52]. Although it is a costly strategy, direct planting offers the best approach for the restoration of the country's TDF where unassisted forest regeneration is not an option [16,31,53]. In other neotropical areas with similar environmental problems, direct planting approaches have accelerated the pace of TDF recovery, while enhancing climate mitigation and the ecological and economic resilience of local communities [54–56]. Likewise, seeding is a practice with a high potential for reforestation. In this review, few studies used seeding as a restoration practice, and none was focused on comparing it with direct planting. Some authors have highlighted that because there are numerous drivers of the success of these two practices, it is not clear when one should be preferred over the other [57]. Further research on this topic is required for the understanding of effective practices in Mexico TDF.

For the studies examined here, the most common land use prior to restoration was agricultural and cattle ranching activities, which is consistent with other studies from the Neotropics [10,47,54,58]. The loss of vegetation cover, soil compaction, the use of agrochemicals such as pesticides and livestock dewormers, crop management techniques such as the burning of sugar cane, etc., have polluted water bodies, reduced air quality, and decreased the capacity of ecosystems to mitigate climate change and provide services such as temperature regulation and prevention of floods and landslides [15,59,60]. For decades, academic and conservation-oriented non-governmental organizations have highlighted the impact of land use on biodiversity, so restoration is also an important conservation strategy. To this end, there has been a recent increase in ecosystem-based adaptation proposals by international agencies such as United Nations (UN) to face the climate change challenges, focused on the recovery of natural resources to support human communities via the prevention of natural disasters and training to diversify income sources [61,62].

4.1. Trends of Restoration Success

The survival of planted individuals is the most commonly used metric of restoration success. In the reviewed studies, the survivorship of outplants in TDF restoration projects can vary from 0% to 80% [15,18,49,63–67]. In other Neotropical countries, such as Panama and Argentina, the reported survival values range between 0% and 95% [9,47,51]. Even though the surveyed restoration efforts were mainly in small areas with short-term experimental objectives, these studies have made it possible to identify robust restoration strategies while also identifying optimal seasons for direct planting and types of additional management that can enhance success. Based on the concept of precision restoration [68], it is necessary to focus management efforts at the plant level, using the lessons learned from previous efforts and available technologies. Some of the management actions that appear to be broadly successful at enhancing seedling survival can now be listed as recommendations for larger-scale efforts. These include (1) fertilization in karstic soils such as in the Yucatan region [18,63]; (2) the use of plastic mulch in the central region of the country (e.g., Morelos State) or in soils characterized by water stress [66,67,69]; (3) the selection of species that combine pioneer and later successional species; (4) a greater genetic and functional variability [31,70]; (5) using nurse trees in the Bajio region [70].

Survival showed high sensitivity to mean maximum annual temperature and the Lang Aridity Index across the reviewed studies. An important future research area is understanding the role of periodic and unanticipated warm spells or droughts in driving low restoration success. Specifically, it is important to determine to what extent low survivorship is a function of unusually dry or warm conditions at a restoration site, and whether sites that are already warmer and drier are more susceptible to such events. If there is a connection between especially low survivorship and anomalous climate events, then investments in better climate prediction to managers may be needed to effectively guide the timing of planting or identify a need for additional practices that can assure water availability. Given the time it takes to collect and propagate seeds, advanced drought warning systems are especially valuable, for example, identifying potential rainfall patterns based on multi-year El Niño-Southern Oscillation estimations.

The lack of relationship between survival rates and soil fertility in our analyses contrasts with previous studies in diverse TDF regions including Mexico, which have found that the carbon–nitrogen ratio (C: N) was correlated with planting survival [49,63,65,71,72]. In TDF of India and Thailand, soil microclimatic conditions have been found to be important correlates of seedling survival [50,73]. For places where the initial conditions are unfavorable for plantings, success could be increased by preparation practices such as the removal of unwanted plants such as invasive grasses [74,75], soil reclamation, the establishment of artificial shade areas to reduce evapotranspiration, or implementation of low-cost actions such as artificial perches to favor the arrival of seed-dispersing species [26,76]. We found that, unsurprisingly, rainy season plantings showed higher survival rates than dry season plantings, though the impact of seasonality decreased when plantings were irrigated. In other cases, the use of fertilizers or mulches can enhance survival [18,49,66,69]. In regions such as the Caatinga in Brazil, some strategies for recovery of soils and vegetation included the use of nurse trees to enhance microclimate conditions, the use of litter from adjacent intact forest to recover mycorrhizal fungi and provide mulch and nutrients, and mixed plantings including endemic species [77–79]. These strategies seek to reduce the impact of water limitations on seedling survival and growth.

There were too few studies comparing low- versus high- diversity plantings for us to formally analyze the impact of planted species diversity on survival rates, but previous research has shown that mixtures of species tend to have higher survival rates than single-species plantings [31,48]. This may be because planting several species increases the likelihood of planting at least one that is well suited to a site or site conditions [48,49,80,81]. Some authors have highlighted the need to incorporate a functional attributes perspective into the selection of species for restoration projects [80]. For example, Ceccon et al. [60] found that soil recovery could be achieved using species mixtures that include members of the Fabaceae, such as *Pithecellobium dulce* or *Leucaena leucocephala*, which have rapid growth and quick canopy closure and produce abundant nutrients, especially nitrogen-rich litter. The Yucatan Peninsula provides another example of the importance of species selection where three primary forest species (*Brosimum alicastrum*, *Enterolobium cyclocarpum*, and *Manilkara zapota*) were used to successfully accelerate structural and compositional recovery [16]. Clearly, there are multiple avenues to increase the success of direct planting, and there is a need for expanded site-specific research into next-generation prescriptions for TDF. Making informed decisions when planning, designing, implementing, and monitoring success in a restoration project enhances the probability of ecosystem recovery while reducing costs [31,55]. By identifying the advantages, disadvantages, and site specificity of different practices, more appropriate and adapted projects can be promoted for each context. Additionally, defining the logistical, ecological, and social elements is useful to the development of restoration projects.

4.2. Are Current Restoration Initiatives Enough?

The Mexican government has increased investment in the restoration of forest ecosystems, which has been reflected in the signing of high-level international agreements. Some of the efforts have focused on different government entities that have estimated the Anthropic Impact Index and Ecological Degradation Index of Mexico's diverse TDF ecosystems, thus categorizing sites with respect to restoration priority [42,82]. Larger-scale efforts have also developed prioritization schemes for TDF restoration across Latin America [83,84] and highlight the importance of understanding landscape variables (e.g., connectivity) and human impact (e.g., degradation due to land use) for selected restoration sites. However, multiple sectors have recognized that <1% (~28,000 ha) of the TDF biome has recovered a forest canopy, which is insufficient to meet Mexico's larger environmental goals. Legislated restoration mandates will inevitably result in expanded restoration of the TDF in Mexico, and our findings suggest that this expansion will benefit from strong investment in the science of restoration, including the identification of cost-effective and site-specific restoration practices—recently defined as precision restoration [68]—or more general practices optimized for a wide diversity of sites. By developing a TDF restoration framework for Mexico, national-scale restoration planning can help to more effectively prioritize restoration investments into projects that are most likely to succeed [46,55,85]. This framework would further help resource managers to identify practices and prescriptions that are suitable given the climatic, edaphic, and ecological condition of a site to avoid applying more generic practices that may not lead to successful or timely restoration. This framework would also serve restoration practitioners well by providing easily implementable monitoring ideas with metrics that are simple to understand and interpret.

Mexico does not currently have a long-term national plan for the ecological restoration of its ecosystems. However, in the region, there are examples that aim to remediate environmental situations similar to those faced by Mexico, such as deforestation, invasive species, overexploitation of natural resources, pollution, and climate change [86,87]. Large-scale restoration frameworks have focused primarily on seven principles: (1) a landscape approach is necessary to restore ecological functions; (2) taking into account the local-territorial context of local communities to understand their needs; (3) generation of instruments for planning, designing and monitoring restoration projects; (4) promoting local and national economic sustainability; (5) promote participatory governance that allows transparency and credibility of projects; (6) guaranteeing management and incorporation of ancestral, cultural and technical knowledge; (7) having a solid normative structure that shields projects and their goals. The experience of the regional guidelines for national restoration allows us to identify that it is necessary to develop an action plan based on existing efforts.

Moreover, direct planting is logistically and economically costly and shows variable success rates [15,31,49,63]. Direct plantings of native species have also been used as part of the efforts carried out by the government, mainly using only one species with fast growth rates, such as *Cedrela odorata* [88]. However, considering the lack of planning instruments, in many cases, the implementation of forest restoration plantings promotes the replacement of natural ecosystems, such as grasslands or natural shrubs [45,60]. We also identified that a large part of TDF restoration efforts in Mexico are carried out in semi-arid sites with low soil fertility, so direct planting may not always be a suitable option. Additional management (e.g., irrigation, fertilizer) to maintain planted seedlings under arid conditions may increase the costs of the initiative without increasing the probability of success [50,71,89,90]. These types of experiences, knowledge, and data must be collected and analyzed to generate the basis for a national restoration plan. It is important to recognize that TDF restoration efforts in Mexico need to increase in number and extent to compensate for the high rates of transformation and disturbance.

4.3. Ecological Restoration Needs Society

In Mexico, 43% of the land base is controlled through collective land concessions, or "ejidos", which support a wide diversity of communities including 68 indigenous groups [45]. Approximately 47% of the restoration initiatives we reviewed occurred within these ejidos, highlighting the importance of socio-cultural factors in designing and sustaining restoration projects. However, as with previous Mexican and the Neotropical TDF studies [45,47,91], our review included only two studies that considered social drivers of restoration practice of success. In most of the restoration efforts in the Neotropics, the communities are included in the execution phase, as support in the fieldwork and the monitoring of progress. In a few cases, local communities are consulted for the project design, mainly with regard to site and species selection [54,92]. Studies that included social aspects in the restoration project did not combine ecological metrics and vice versa, which makes it difficult to integrate social and ecological dimensions of the restoration process [92]. Ideally, future studies will increasingly include both ecological and social dimensions of restoration efforts [15,59,93]. There are calls for increased recognition and engagement of communities in the planning and development of TDF restoration projects, in order to enhance project success in the recovery of ecosystem biodiversity and function to meet the needs of local communities [45,47,49,91].

4.4. Implications and Future Direction

The main implications of this study in the ecological restoration of the TDF in Mexico are focused on an attempt to synthesize the information of restoration efforts and the analysis of restoration success. We described the climatic contexts in which TDF restoration efforts are carried out in Mexico, which we related to the probability of success that some projects had. This allowed us to make an initial approach in the identification, within a climatic context, of the strengths and weaknesses of some of the strategies reported in the reviewed studies. Likewise, we provided evidence of the need for a precision restoration, which encompasses the knowledge generated in previous experiences and promotes the development and use of technologies to increase the probabilities of success of the restoration strategies based on environmental similarities between specific sites. Mexico must move towards a solid and inclusive national proposal for the restoration of its ecosystems. This review, together with other efforts, constitutes one of the first steps towards that goal.

5. Conclusions

The purpose of this study was to discuss the current knowledge about the restoration strategies of TDF in Mexico and to understand the impact of national efforts within the framework of the international restoration commitments signed by the country. From our analysis, it is clear that important efforts have been made to evaluate different practices and management for the recovery of the ecosystem, but we also provided evidence for the need to scale these efforts from experimental plots to restoration regions. Currently, there is sufficient information to establish a national restoration framework with the most efficient strategies, and the management that should be avoided based on the conditions of previous use, aridity, fertility of the soil, precipitation regime, maximum annual temperature, etc. We also identified the need to make a greater integration of different stakeholders and social dimensions to evaluate the impact of ecological restoration projects, promoting projects that encompass the needs of human communities. In order to achieve a reference framework and a national restoration plan, government agencies, stakeholders, and academics must be able to define the basic principles that allow them to find a meeting point for the coordination of solid, long-term projects at the landscape scale. This will allow Mexico to meet its restoration goals and enhance ecosystems with the capacity to adapt and mitigate climate change, which will be reflected in human well-being and the ecological functionality of landscapes.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14073937/s1, Figure S1: Review method diagram, Table S1: Soil types and fertility category of the studies that had fieldwork, both in experimental studies and implementation of active restoration, Table S2: Description of the categories of the metrics reported by the studies reviewed to evaluate the impact of the restoration studies. The variables that were included in each category are specified, Table S3: Information on previous land uses reported in the studies, as well as the categories of active restoration strategies recorded in the reviewed studies, Figure S2: Frequency of studies in the different categories of duration of the implementation of a restoration strategy (yr), Figure S3: Relationships between plant survival and environment variables: (a) total annual precipitation (mm yr^{-1}), (b) minimum annual temperature (°C), (c) mean annual temperature (°C), (d) mean evapotranspiration (mm), (e) elevation (m), (f) anthropic impact index, and (g) ecological degradation index.

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