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Review

The Pine-Oak Forest of the Rio Conchos Basin, Mexico: Key to Rain Production and Soil Erosion Control

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Abstract: Under the current climate crisis, the ecological integrity of forest ecosystems is key to increasing resilience and the sustainability of water and soil resources. Most forests around the world have experienced deforestation and degradation in the past few decades; however, the rate at which these occur varies depending on many factors, including the type of trees, management, and climate. We conducted a review of the deforestation, degradation, and soil erosion of the pine-oak forest within the Rio Conchos basin in northern Mexico. Preference was given to recent studies (last 10 years) conducted within this basin. Out of 27 recent publications on oak forests in Mexico, 19 focused on this forest and half of them were in Spanish. The results show that pine trees are more affected than oak trees, also that the deforestation rate has increased with time and is greater at higher elevations, making this area vulnerable to loss of topsoil during extreme hydrological events. Studies report an annual change in cover rate between 1985 and 2016 of −1.2% for pine, oak and mix vegetation. More recently, between 2000 and 2018, the change in pine cover was calculated as −2.8% concurrent with a +3.4% increase in cover of oak and other secondary vegetation. Proposed conservation strategies vary from runoff control to increased collaboration between landowners, government agencies, and stakeholders.

Keywords: global climate change; Chihuahua; pine forest; runoff; water capture

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1. Introduction

Forest ecosystems are widely recognized as providers of many beneficial functions to global climate, to the environment, and to biodiversity [1–5], including their contribution to local rainfall and their ability to redistribute the sun's energy, enhance infiltration, and purify water [2]. Forests increase resilience in an area because of the trees' ability to store carbon and to anchor soil that otherwise would be lost during intense precipitation events [6], which are expected to occur more often because of global warming [7]. Despite the important functions the forests provide, deforestation is a common and persistent problem worldwide [4,8]. The cause of deforestation can be natural (forest fires, landslides) or anthropogenic (illegal logging, removal of trees for farming, removal of trees for urban development) [9,10].

Sadly, the connection between forest ecosystems and water and energy cycles is poorly integrated into decision-making at local, national, and continental levels, especially when related to adaptation to global climate and mitigation of its effects [4,11,12]. In addition, the information reported for these ecosystems is highly fragmented in place and time, making it difficult to know the extent of the problem [13] and, in some cases, masking the problem. An example of the latter would be reforestation with single species or non-native species, which are less beneficial than natural forests [6,14,15]. Insufficient data about the forest ecosystems thus hinders the capability to protect the climate and natural resources [13,16,17].

Notable organizations and programs dedicated to the conservation of forest ecosystems include U.N. Food and Agricultural Organization (FAO), Global Forest Watch (GFW) an online platform that shows forest coverage in real time using remote sensing (satellite) information, and the World Wildlife Fund (WWF) that protects vulnerable environments. In Mexico, government programs dedicated to the preservation of forests are mainly housed in the agencies CONFOR and CONABIO. The problem of degradation has been identified as an urgent problem by all the above agencies and one that should receive immediate attention. The United Nations designated 2020–2030 the decade of ecosystem restoration, prompting world leaders to aid in recovering degraded ecosystems, most of these forests. Academics have responded to this need by shifting the scope of investigations to a more holistic approach in forest investigations, i.e., including interactions with biodiversity, climate, soil loss, etc.

Recent studies [3,11,18–21] have contributed evidence towards the generalized perception that trees simulate and produce precipitation, and mention that, on average, 40% of precipitation on land originates from the evaporation and transpiration of plants (Figure 1) [18–20]. In this context, forests are not limited to growing in humid climates, but they develop and maintain humidity on their own, reducing the length of the dry season [20].

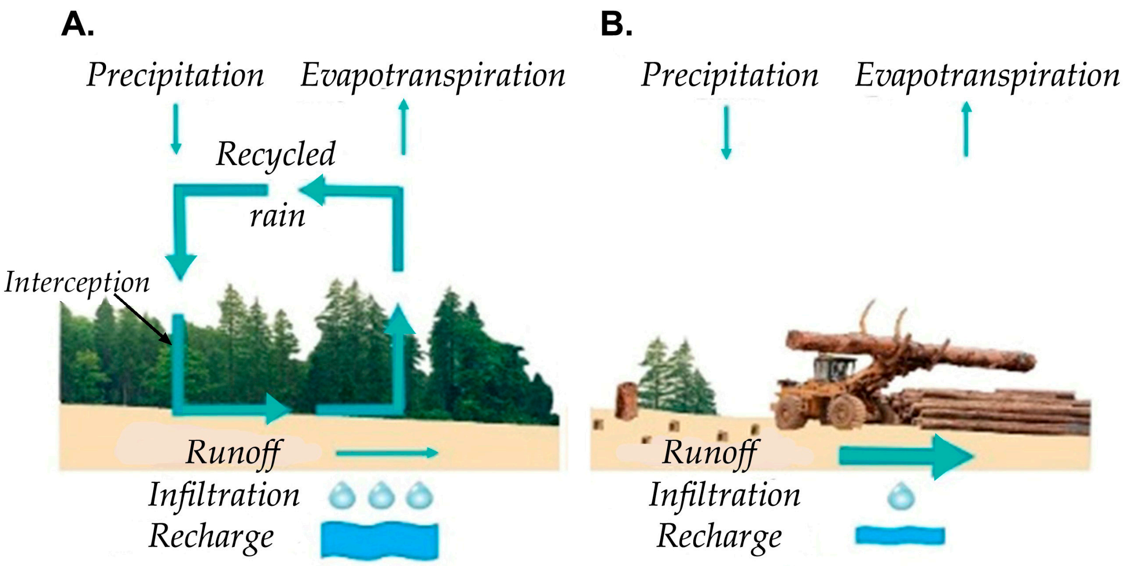

Figure 1. Schematic diagram showing (**A**) a natural forest and (**B**) the effects of deforestation on precipitation, runoff, infiltration, and recharge. (Figure by the authors).

Trees enable water interception, infiltration, and the recharge of aquifers, allowing groundwater to naturally disperse and, in this way, help slow down runoff, lessen hydric erosion, and prevent flooding [3,10]. On the other hand, when substantial amounts of vegetation are removed, the wet season is delayed, there is less available water to provide evaporation and transpiration, and precipitation events are suppressed by a considerable amount [3,9].

Soil loss by hydric erosion is a severe problem at a global scale that threatens food security as well as aquatic and terrestrial ecosystems [6,10,22]. The soil erosion rate depends on various factors, including land use, slope, and intensity of precipitation [23]. With respect to land use, erosion is greater in agricultural zones compared to forested zones [13,24]. The increase in intensity in the hydrologic cycle associated with global climate change and a broader surface area devoid of trees are thus expected to cause a significant increase in the soil erosion rate [1,23,24]. Mathematical models predict a global increase in hydric soil erosion ranging between 30% and 60% for 2015–2070 [22]. In sum, maintaining healthy forest ecosystems cannot be relegated to second place anywhere in the world since forests provide reliable access to water, tolerable atmospheric temperatures, lessen the loss of topsoil erosion, and maintain ecological integrity.

This paper focuses on the Rio Conchos basin of northern Mexico. Much of the importance of this basin is that the Rio Conchos runs through a desert before reaching the Rio Grande at the Mexico-USA border, providing critically needed water throughout its journey. The water this river carries is insufficient to cover the demand of the many users within the basin and downstream, often creating disputes among them. Deforestation within the basin and a more intense hydrologic cycle further threaten this river [14]. Conservation of the forest, which covers about 28% of the basin, could help ease the problem by capturing rainwater and building resilience against global climate change [14,16,25]. Despite the importance of the forested part of this basin as a provider of downstream water, little information is available about its degradation and soil erosion status, except for a few recent reports. This review incorporates the results from 19 papers reporting on this forest, 90% of them written within the past 6 years; however, half of them were in Spanish. This review compiles their results and directs investigators to the source for more detailed information. The objectives of this review are (1) to analyze the present status of deforestation and soil erosion within the Rio Conchos basin via a review of recent regional and international publications, and (2) to analyze and compile conservation strategies recommended by the aforementioned authors as well as exploring the potential for implementing them.

2. Methods

2.1. Study Area

The Rio Conchos is the most important river of the state of Chihuahua, traveling 560 km from its source in the heights of the Sierra Madre Occidental to its mouth as it merges with the Rio Grande at the Mexico-USA border. During its travel, it crosses desert plains where water is utilized for agriculture, and feeds aquifers that are used as drinking water sources for about 1.5 million people (Figure 2).

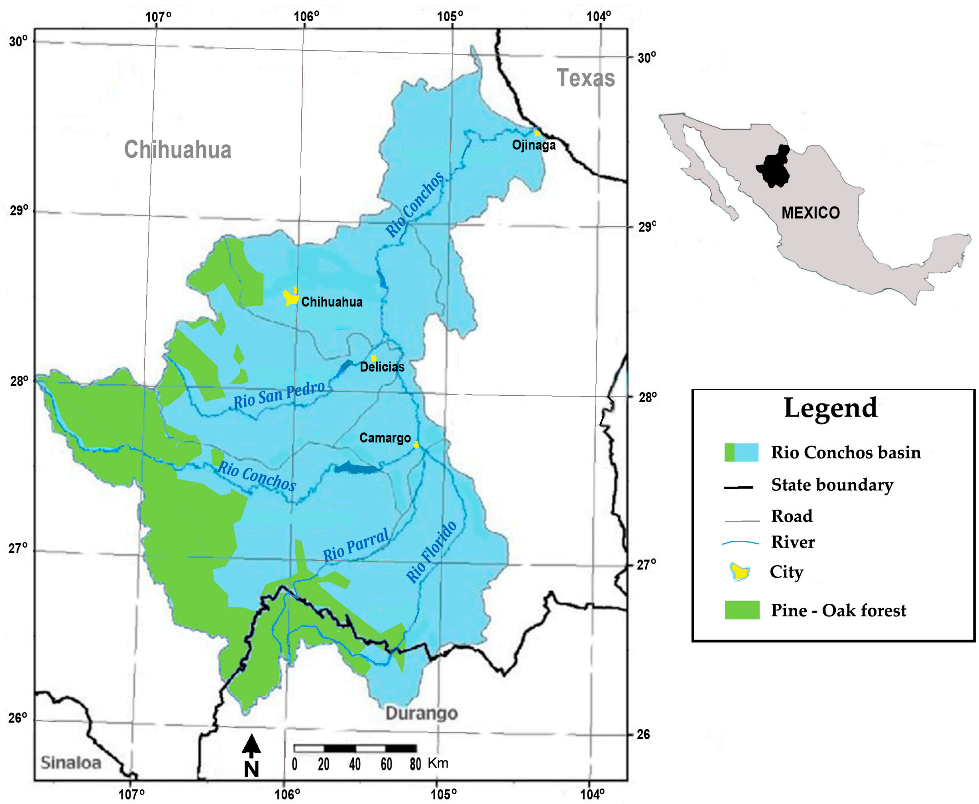

Figure 2. Rio Conchos basin and location of pine-oak forest.

The Rio Conchos basin extends over 37 counties (municipios), 34 of which are in the state of Chihuahua and 3 in the state of Durango, with a total surface area of 6.72 million ha. With respect to elevation and climate, the basin is subdivided into three main parts: upper, transitional, and lower. The upper part of the basin has elevations between 1500 m and 2800 m above sea level and receives an average annual precipitation of 700 mm, more than twice the precipitation of the lower part. The vegetation of the upper part of the basin is classified as a temperate forest and contains several endemic species of pine and oak, covering areas where the slope varies between 10° and 15° [26–28]. Temperate forests occupy about 20% of Mexico's territory and have a high diversity of habitat and species richness [13]. The largest of these forests is located in Chihuahua, and is an important source of timber, a profitable activity with an average volume of 220 m^3 ha^{-1} and an increment in production rates of 4 to 16 m^3 ha^{-1} [29]. There is a large variation among these numbers as some parts of the forest can have stands with 75 m^3 ha^{-1} or 120 m^3 ha^{-1}, depending on stand conditions [29].

Human activities (logging, agriculture, human settlements) have greatly altered this basin, causing problems of deforestation, exploitation of mineral resources such as sand and gravel, and river water contamination [25,26,30]. This basin is also affected by its extreme climate; intense drought periods that may last 5 years or more [17] followed by short-lived, intense precipitation events causing rivers and arroyos to suddenly flood, causing damage to structures and agricultural fields [31].

2.2. Methodology

Despite its economic and ecologic importance, available information on this forest is, for the most part, fragmented and incomplete. Towards this review, publications were searched (Scopus, Environment Complete) for pine-oak forests in the Rio Conchos basin, Mexico. Preference was given to recent studies (2002 to present) and to those conducted in either the Rio Conchos basin or its immediate vicinity. A total of 27 publications were selected, 19 of which were collected within the Rio Conchos basin, and the rest encompassed forests of Mexico by type, not by geographical region. Out of the 19 publications in the study area, 16 were published within the past six years and 10 were in Spanish. The results were compiled from all of these. Quantifiable parameters (deforestation rates, hydric soil erosion rates) were organized into tables for better visualization and to allow comparison.

3. Results

3.1. Reduction in Forest Coverage

In the past decades, vegetation coverage has diminished throughout Mexico, with an annual deforestation rate amounting to 251,000 ha yr^{-1} (−0.19%) between 2010 and 2020 [8], which although better than the past two decades (−0.21% for 2000–2010 and −0.32% for 1990–2000), points to a non-sustainable use of the land [4,27,32]. The unsustainable use of resources is a problem that the various programs and organizations mentioned above are trying to lessen. The deforestation rate is higher in forests for either tropical or temperate climates at an annual rate of −0.76% and −0.25% reported for the interval 1976–2000 [32]. Land use change and deforestation are also reported at the state level, e.g., Chihuahua [33] and Nayarit [34]; or at the hydrologic basin [33,35–37].

Table 1 lists studies reporting a change in forest coverage in the Rio Conchos basin. These studies vary with respect to the period during which the data were analyzed, the classification of the different types of trees (pine, oak, mix), and in the manner which the results are reported, either as deforestation (no vegetal cover) or degradation (reduction in tree density and presence of secondary vegetation). Nevertheless, all these entries contribute to forming a picture of the changes in the forest ecosystem that have occurred during the last 4–5 decades. A study conducted in 2006 in a region within the Rio Conchos basin known as Unidad de Manejo Forestal San Juanito stands out [38]. This study reports an average annual reduction in forest cover of −1% between 1997 and 2005, with a reduction in the surface covered by pine and an increase in oak and mix (pine-oak) cover, agreeing with the reportedly higher resilience of oak compared to pine [28]. This rate of deforestation is considered high, and thus deserving of emergency measures to revert it, generally accomplished after performing various actions towards reforestation [39]. In addition, Martínez-Sifuentes et al. [38] report an increase in pine trees (+0.21%) between 1980 and 2000 within the Rio Conchos basin, whereas, in the period 2000 to 2018, a decrease in the cover of pine and an increase in the cover of oak. A concurrent increase in the agricultural surface cover in both periods suggests that the changes in forest type are likely anthropogenic and related to agricultural production. Changes in pine and oak coverage with respect to time for forests of the Rio Conchos basin were plotted for better visualization (Figure 3). Figure 3 shows that positive values (increase coverage) correspond to mostly oak while and negative values are common for pine. Forest cover rates for the Rio Conchos basin [25,26,38,40] plot within the range of values obtained for Mexico's temperate forests [30].

Table 1. Change in forest coverage reported for the Rio Conchos basin. Deforestation rates for temperate forests of Mexico are listed for comparison purposes.

Zone Period of Study	Forest Cover, in Hectares (ha) (S. = Surface Area, Ch = Change),	Annual % Change	Land Use Change	Reference
Mexico 1976–2000	S. Primary temperate forests 1976: 303,087 Ch: −93,870 S. Secondary temperate forest 1976: 48,954 Ch: +73,058	−1.3% +6.2%	The study includes different types of vegetation cover and compares two periods, 1976–2000 and 1993–2000.	[30]
Mexico 1993–2000	S. Primary temperate forest 1993: 268,499 Ch: −63,074 = −0.23% S. Secondary temperate forest 1993: 84,470 Ch. +38,576	−3.3% +6.5%		[30]
Rio Conchos basin 1970–2000	S. pine 1970: 14,978 Ch: −5162 S. oak 1970: 4109 Ch: +1634	−1.1% +1.3%	Deforestation; forest replaced by desert shrub and agriculture	[26]
Rio Conchos basin 1980–2000	S. pine 1980: 10,327 Ch: +443 S. oak 1980:1515 Ch: −467	+0.2% −1.5%	Increase in pine and agri-culture covers, reduction in grass and oak covers	[38]
Rio Conchos basin 2000–2018	S. pine 2000: 10,770 Ch: −5566 S. oak 2000: 1048 Ch: +6.32	−2.8% +3.4%	Deforestation of pine cover, increase in oak cover	[38]
Rio Conchos basin 1985–2016	Pine, oak and mix S. 2016: 10,970 Ch: −4201	−1.2%	Secondary vegetation S. 2016: 475,760 ha, Change: +250,350 ha	[32]
Five counties in the upper Rio Conchos basin: Balleza, Bocoyna, Carichi, Nonoava, San Fco. Borja, 2000–2010	Change in forest cover −2542	−1.8%	Deforestation and degradation, no distinction made between pine and oak	[40]

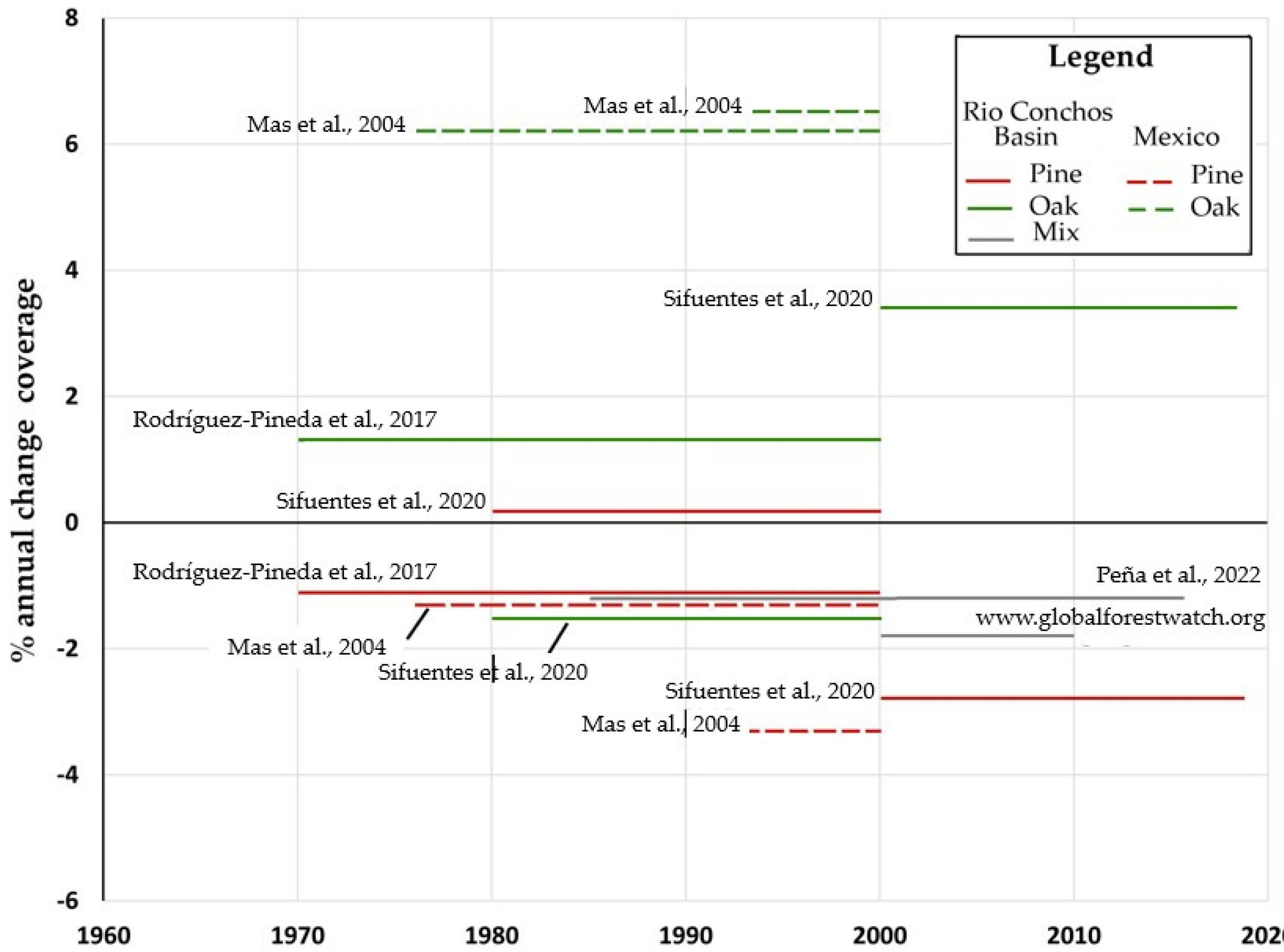

Figure 3. Percent annual change of forest cover reported for the Rio Conchos basin (solid lines) and Mexico's temperate forests (dashed lines) [26,30,32,38,40].

The main causes of deforestation in the upper part of the basin have been identified as forest fires, illegal tree cutting, and drought [39], and pines (*Pinus spp.*) as the trees most severely affected. The loss of pine cover is aggravated by pest insects such as the bark pine beetle, and *Dendroctonus rhizophagus*, which weakens the tree bark and makes trees more susceptible to burn during forest fires [39].

The regeneration of vegetation in the upper basin occurs by natural processes and may be induced by the reforestation of nearby disturbed areas where conservation practices are being implemented [41]. However, in transitional parts of the basin, where there are grazing cattle, regeneration is sparse and receives no protection, maintenance, nor monitoring [4,15,32].

3.2. Hydric Soil Erosion

According to official reports, in 2001–2002 [42], 12% of the total surface area of the state of Chihuahua was affected by hydric erosion and 25.9% by eolic erosion. Hydric erosion results in the deformation of the ground (Figure 4) and the reduction of topsoil [31]. Reports on hydric erosion within the Rio Conchos basin are listed in Table 2. Soil loss in the years 1980, 2000, y 2018 after high to very-high rates of erosion affected 0.060, 0.018 y 0.100% of the total basin surface, respectively [38]. The year 2018 was very susceptible to soil erosion, with 6718 ha of the affected area after experiencing a runoff five-fold those of the year 2000 and twice those of 1980 [38].

Figure 4. Soil erosion by water and terrain deformation (photos by the author).

Table 2. Hydric soil erosion within the Rio Conchos Basin.

Study Area	Soil Erosion, in Metric Tonnes ha^{-1} $year^{-1}$, or % Surface Area	Change in Land Use	Ref.
Rio Conchos basin 1980–2018	1980: 1.45 2018: 2.47	increase in pine forests, reduction in oak forest in 1980–2000; opposite results in the 2000–2018 period	[38]
Rio Conchos basin 1960–1983 vs. 1894–2008	Increment of minimal flows in dry season and increase in the duration of high flow pulses	Variation of precipitation pattern both in high flow pulses and low flow pulses, conducive to an increase in soil erosion rate	[43]
Rio Conchos basin 1960–1983 vs. 1894–2008	Increase in extreme values of drought and precipitation in the past few decades, $\lvert SPI \rvert > 1.5$,	Analysis based on the normalized precipitation index SPI	[44]
Chuvíscar-Sacramento basin 2000–2017	Increase in runoff depth, higher in zones with a decrease in forest cover	Decrease in forest cover from 614 km^2 in 2000, to 540 km^2 in 2017	[35]
Estado de Chihuahua 2001–2002	% surface area affected by hydric erosion: Severely affected: 0.10% Degraded: 12.0%	% surface area affected by physical erosion: Severely affected: 0.18% Degraded: 4.0%	[42]

At a global scale, the lapse between extreme forest fires like those occurring in Australia and the Amazons in 2021 is shortening, causing abrupt and significant disruption to the ecosystem. In this respect, the Rio Conchos basin is not an exception and experiences intense forest fires more often, resulting in severe damage to existing vegetation. Forest fires are reportedly the main cause (50%) of deforestation in the upper basin [28]. On a sub-basin scale, a decrease of forest cover of −7717 ha in the Chuvíscar-Sacramento basin between 2000 and 2017 [35] and modeled rain of an intensity of 62 to 88 mm may cause an increase in runoff large enough to overflow the stormwater infrastructure of the city of Chihuahua and cause significant flood damage.

4. Recommended Actions towards Protecting the Forest Ecosystem

4.1. Potential for Reforestation in the Upper Rio Conchos Basin

In the upper Rio Conchos basin, an estimated 166,000 ha are reportedly available for reforestation, resulting from land use change and a decrease of forest cover [37]. However, there are various barriers deterring the reforestation of these areas, including: (a) the impacted areas require a considerable amount of funds to recondition the ecosystem in order to apply reforestation as areas may contain a significant amount of dead vegetation, and in many instances the ground is covered by manzanita (*Arctostaphylos pungens*), (b) the variability in climate and the intense hydrologic cycle that has resulted from global climate change greatly limits the establishment of new plants, also evident by the lack of rain and snow during the past few winters, (c) lack of environmental education in the impacted communities that limits their participation in caring for and maintaining forests [25], (d) grazing is common in most of forested areas, which may lead to soil compaction and cattle browsing which in turn destroy the newly planted vegetation, and e) lack of enough saplings of the type and quality required, as many times a large number of these are required at once.

An element to ponder is the planning of the technical activities such as pre-thinning, thinning, and plant density at stand level for effective reforestation, as well as the best possible reduction of competing species and redistribution of moisture (Figure 5). These are in order to increase resilience to global climate change, that is, to improve the recovery capability of trees, making them stronger to deal with pests and extreme forest fires [12,45,46].

Figure 5. Managed pine-oak forest, upper Rio Conchos basin, at 21% thinning. (Photo by the author.)

Prevention and conservation measures such as the opening of firebreaks and black lines for forest fire control (Figure 6). Thinning is a common treatment, that once properly done, increases the resilience of forests against global climate change, as it produces an increase in net precipitation, reduces runoff, recharges aquifers, and mitigates the effects of drought [23]. Although the results vary for each region and type of forest, 50% thinning is a rule of thumb when negative effects become evident. At any degree of thinning treatment, monitoring is needed to check that soil degradation and water quality of runoff are within recommended values [23].

Figure 6. Preparing terraces for reforestation. (**A**) stone barriers, (**B**) water catchment, (**C**) trench ditches, and (**D**) filter dam [47].

4.2. Computer Modeling

The response of the ecosystem to various forest management actions can be predicted using computer modeling according to possible scenarios. The results of using a particular set of conservation measures can be compared to those without conservation, or business-as-usual [4]. For example, Mendoza et al. [4] used the LUCC model to predict areas prone to change and found that secondary vegetation in Mexico under conservation management would be reduced from 26% to 21% in 2050, but without conservation, would expand from 26% to 37% in 2050. The response to tree density and tree diversity to conservation measures can also be assessed by means of experimental plots [27]. Under this methodology, various plots are applied to various degrees of management, and the resulting importance value index (IVI), diversity, and evenness are measured for each treatment. Monarrez-Gonzalez et al. [27] used this method for three treatments (100%, 60%, and 30% removal of the basal area; where 100% is clear-cut) in a pine-oak forest in the vicinity of the Rio Conchos basin and found five tree species of pine and oak that had high IVI and that semi-intensive treatments did not affect tree diversity in a significant way.

4.3. Non-Traditional Methods

Non-traditional conservation measures that add resilience to the forest environment include the assisted planting in higher elevations of tree species that regularly grow at slightly lower elevations [48], planting saplings close to the edge of the canopy instead of clearing gaps so that saplings benefit from the nurse effect of trees, reduction of livestock pressure to allow saplings to survive, and alternative regeneration methods such as the irregular group shelterwood method [16]. A way to measure the ability of the forest to intercept and infiltrate water consists of measuring stemflow and runoff and determining their association with one or more of the forest variables: tree diameter at breast height, basal area, canopy coper, and volume [49]. Stemflow in pine-oak forests of northern Mexico was more significantly related to the diameter at breast height whereas runoff was found to be inversely proportional to the basal area [49].

Other usually conducted management measures consist of checking for potential plant pests and forest diseases, stocking plants or saplings for reforestation [47], and training personnel in the conservation and monitoring of forests. These actions correspond to an ideal situation; however, reality shows problems in implementing management practices, some of the most common include: forest conservation policies that are not clearly delineated or followed, poor communication among government forestry agencies and stakeholders as well as among stakeholders, and lack of monitoring [26,38].

Fortunately, inhabitants of the Rio Conchos basin are becoming increasingly conscious of the importance of the interconnection between the different ecosystems within a drainage basin and the importance of forest ecosystems in the production of water and soil conservation as well as its role in maintaining biodiversity, all of which benefit the whole basin. Evidence of this improvement in valuing the importance of the forest ecosystem was the cooperation agreement signed in June 2022, the first in its kind in this region, between Chihuahua (state), Delicias (municipality), and CONAFOR (national forestry agency), in which the parties agreed on reforesting 5300 ha in the upper part of the basin. However, much remains to do in the social aspects of forest conservation, such as in-depth interviews with stakeholders and the application of quantitative methods [25].

5. Conclusions

Forest ecosystem studies conducted in the Rio Conchos basin agree that deforestation continues the increase, is more severe in the upper basin, and that pine forests are more affected than oak forests. Forested areas that have been degraded are located on a slope, which makes these areas vulnerable to a more intense hydrological cycle associated with global climate warming, which in turn is expected to increase soil erosion rate, a cycle of negative impacts that will likely magnify with time. Other factors that contribute to deforestation, such as forest fires and the propagation of the bark beetle, are also accentuated by global warming. The surface area at risk of degradation has been reported as 6% of the total surface area of the Rio Conchos basin. The results bring to light the urgency to break this cycle by finding ways to mitigate ecosystem degradation.

The studies report data fragmentation and lack of articulation among the ecosystem needs and the actions taken, arguing that the efforts from government agencies are insufficient and come at a high cost. They go further to recommend various possible solutions, from the control of runoff to a forest management plan where the landowners collaborate closely in the management and conservation of forest resources. Also mentioned is the importance of the full cooperation of community leaders and a community properly informed of the proposed conservation strategies.

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