JOURNAL OF QUATERNARY SCIENCE (2024) 1–13 ISSN 0267-8179. DOI: 10.1002/jqs.3676

JQS Journal of Quaternary Science QRA Quaternary Research Association

Exploring soil erosion in the lake basins of Michoacán, Mexico: From sediment cores to conservation policies

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Received 21 April 2024; Revised 20 November 2024; Accepted 21 November 2024

ABSTRACT: Understanding soil erosion, its history and links to potential drivers such as land use (particularly agriculture and deforestation), different cultural perspectives and climate change are crucial for the development of effective management and conservation strategies. Here, we explore soil erosion in two lake basins, Pátzcuaro and Zirahuen, in the highlands of Michoacán, Mexico, weaving together scientific enquiry (including lake sediment studies and monitoring data) and cultural–historical perspectives based on documentary sources. Both lake basins are within the Trans Mexican Volcanic Belt, lying at >2000 m a.s.l. Pátzcuaro is large, but shallow, while Zirahuen is smaller, but deep. Archaeological evidence for long-term human occupation is clearer for Pátzcuaro. Pátzcuaro is known for severe degradation of both the catchment and the lake, while Zirahuen has, until recently, been regarded as less disturbed. The relative impacts of pre-Hispanic and post-Hispanic practices have been the subject of debates across the disciplines and have impacted approaches to conservation, particularly attitudes to indigenous land use practices. Palaeoenvironmental records highlight human impact on these basins, often expressed as periods of accelerated erosion in response to forest clearance, over at least 3500 years. This shows that neither can be regarded as pristine and were not pristine at the time of the Conquest. As well as responding to varying intensities of land use, often linked to population change, erosion relates to climate, but is also affected by cultural and socio-economic contexts and discourses. Historical documents show that concerns about deforestation and erosion have influenced the development of forest conservation policies, in the context of government reforms, tensions between agricultural expansion and forest conservation, and the growth of scientific research in limnology. These policies have also been shaped by changing cultural discourses regarding indigenous land management practices. The value of taking an holistic approach to understanding erosion is emphasized.

KEYWORDS: cultural perspectives; deforestation; human occupation; indigenous knowledge; palaeoenvironment

Introduction

Soil erosion is a critically important phenomenon in the dynamics of landscapes, especially in areas sensitive to climate change and with a long history of human activity and land use, such as the lake basins of Michoacán in the volcanic highlands of west-central Mexico. Across Mexico as a whole, around 40% of the country suffers from some level of erosion, more than 50% due to surface runoff (CENAPRED, 2020). It is estimated that about 27% of the area of Michoacán is affected by erosion of this type (SAGARPA, 2016). For nearly a century, erosion within the lake basins of Michoacán has been the focus of considerable attention due to the long-standing human presence and land use practices. As well as concerns about the implications of erosion for basin ecosystem health and productivity, it has also been implicated as a driver of lake level change separate from climate and water abstraction (e.g. Bernal Brooks and MacCrimmon, 2000a; Tapia-Vargas et al., 2000).

In the mid-20th century, anxiety about the environmental status of these basins, particularly related to soil erosion and deforestation, emerged as a pivotal catalyst for scientific research and the implementation of forest conservation policies. Within this context, indigenous land systems became a central topic of debate, particularly in Lake Pátzcuaro. In the region, cultivation of sloping terrain (often using terracing) and shifting practices, such as slash-and-burn agriculture, had historically been practised due to the scarcity of flat land. This means that forest and agricultural landscapes frequently overlap, resulting in hybrid landscapes. However, conservation agencies at the time viewed this hybrid practice as contributing to deforestation and erosion, despite their historical adaptation to local landscapes.

The issue of erosion and indigenous land-use practices also surfaced in early anthropological and cultural geography studies (Foster, 1948; West, 1948; Brand, 1951). Deforestation and erosion were identified as pressing issues affecting the Lake Pátzcuaro basin (Foster, 1948; West, 1948; Brand, 1951). West (1948, p. 11) regarded the cultivated slopes surrounding Lake Pátzcuaro as one of Mexico's worst eroded agricultural areas. Foster even referred to erosion as 'Mexico's number one problem' (Foster, 1948, p. 24). According to Brand (1951), multiple factors contributed to erosion in the Lake Pátzcuaro basin, including steep slopes, rainfall patterns and the depletion of surrounding forests due to extensive use by various native industries. These studies were closely linked to broader national and international efforts during the mid-20th century, to modernize the Mexican countryside (Wright, 2012).

The topic of erosion and indigenous land-use systems regained prominence in the late 20th century in both public

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and academic debates. During this period, the focus was on pre-Hispanic erosion and the environmental consequences of the Conquest (O'Hara et al., 1993; Endfield & O'Hara,1999b; Fisher et al., 2003; Fisher, 2005). This was framed by the revision of the 'pristine myth' (Butzer, 1992; Denevan, 1992), consisting of the belief that the landscapes of the Americas in the 16th century were primarily pristine and wild and the idea that indigenous pre-Hispanic practices were predominantly conservationist in nature, known as the 'Ecological Indian myth' (Krech, 1999). These narratives, it has been argued, obscure the complex ways in which indigenous people interacted with their environments based on their needs and cultural values, as well as the sociopolitical and ecological contexts in which they are enmeshed (Gómez Pompa & Klaus, 1992; 1999; TallBear, 2000).

Focusing on Mexico, Denevan (1992) challenged these views by suggesting that erosion was not solely attributable to the introduction of European management systems, but a characteristic feature of the landscapes of Central Mexico. The environmental histories that emerged from this debate showed that indigenous people significantly transformed their landscapes complicating common assumptions regarding the character of indigenous and Spanish land-use systems (Butzer, 1993). However, rejecting the notion of a pristine environment and the stereotype of the 'Ecological Indian Myth' also led to the devaluation of indigenous or traditional ecological knowledge and its contemporary relevance, as well as undermining indigenous sovereignty over their territories (Fisher, 2005; Feit, 2007; Denevan, 2011). This highlights the need for a more nuanced understanding of indigenous practices as responsive to specific ecological, political, cultural and social contexts, rather than categorizing them as strictly conservationist or destructive.

This article explores soil erosion within this intricate context, using an approach that integrates palaeoenvironmental and historical perspectives. We draw on lake sediment and archaeological studies to provide a long-term perspective on the links between changes in erosion rate, human settlement and land cover, and responses to climate change. For lake sediments, key indicators are rates of sediment accumulation, mineral magnetic properties indicative of different source materials and pollen as a record of land cover change. For the colonial and post-independence periods we draw on documentary sources, including historical archives, government records and institutional reports, providing a comprehensive view of land-use changes and conservation policies in Michoacán. Key sources included the Archivo General de la Nación, the Archivo Histórico del Poder Ejecutivo del Estado de Michoacán, and reports from the Forest, Hunting and Fishing Department. Additionally, decrees from the Diario Oficial and debates from the Constituent Congress informed the analysis of early conservation efforts. Mid-20th century studies, such as those by Foster (1948) and West (1948), further shaped understanding of deforestation and erosion in Lake Pátzcuaro. These written sources shed light on the socio-environmental dynamics and the development of conservation policies in the Lake Pátzcuaro and Zirahuen basins and help to reveal the cultural discourses that shaped perceptions and actions around indigenous land management practices, conservation and resource use, including forestry and fishing. We specifically analyse the relationship between these perspectives and conservation policies and the socio-environmental dynamics of the Lake Pátzcuaro and Zirahuen basins from the 20th century onwards. The interplay between soil erosion, climate and other human stressors of these lake systems is also considered, as are the challenges of attempting to take this sort of approach.

Michoacán's Lake Basins

The State of Michoacán, in the Trans Mexican Volcanic Belt, has numerous lakes, ranging from large, currently shallow lakes such as Cuitzeo, to small, deep, crater lakes such as Los Espinos and La Alberca de Tacambaro (Fig. 1). Today, these lakes are largely hydrologically closed (endorheic) with no surface outlets and fed mainly by rainfall and groundwater. Soils developed on this volcanic geology are predominantly andosols and luvisols, which although fertile, are highly susceptible to erosion (Chacón Torres, 1993). The evolution of these basins has been determined by tectonic and volcanic activity (Israde-Alcántara et al., 2005), climate change (Metcalfe et al., 2007) and human activity. As described above, the balance of these processes, particularly how they might be expressed through changes in soil erosion within the lake catchments, has been the subject of long-running debate, with implications for our understanding of archaeology, history and catchment management.

Figure 1. Location of main lake basins and key volcanoes in Michoacan and the central volcanic highlands. [Color figure can be viewed at wileyonlinelibrary.com]

Cuitzeo, Pátzcuaro and Zirahuen (Fig. 1) are the largest of the present-day lakes, arranged along a topographical gradient, with Zirahuen at the highest elevation (2075 m a.s.l.), Pátzcuaro at 2035 m a.s.l. and Cuitzeo at 1840 m a.s.l. Another extensive lake in the past was Zacapu, but this was largely drained at the turn of the 20th century (Guzmán Ávila, 1985; Reyes, 1991).

In this paper, we focus on two of the most intensively studied of the Michoacan lakes: Lake Pátzcuaro and Lake Zirahuen. Lake Pátzcuaro (19°25′N, 101°26′W) is generally shallow, with depths of less than 12 m. The basin covers an area of 929 km^2, with the lake itself occupying ~72 km^2 (Medina-Orozco et al., 2019). The lake has high pH and alkalinity, high turbidity and high levels of nutrients (being eutrophic and hypereutrophic in the north) (Chacon Torres, 1993). Erosion of sediments from the upper to the lower slopes of the catchment has been estimated at up to 140 million m^3. In contrast, Zirahuen (19°26′N, 101°44′W) currently has a maximum depth of >40 m. The basin extends over an area of 283.9 km^2, with the lake occupying ~9.7 km^2 (Ortega et al., 2010). The lake has high pH, is slightly alkaline and of generally low turbidity (Davies et al., 2004). Traditionally classified as oligo- or oligo-mesotrophic, the lake has been becoming more eutrophic due to increasing inputs of N and P, associated with agriculture and household waste. Lake transparency has been reducing (Bernal-Brooks et al., 2000b). Soil loss across the basin is predominantly classified as low (<3.0 t ha^{-1} a^{-1}) (Bravo Espinosa et al., 2009), but erosion and gullying are clearly evident (Fig. 2).

Although sub-tropical, the elevations of the Pátzcuaro and Zirahuen lake basins mean that their climate and vegetation are not typically tropical. Their climate is classified as temperate sub-humid, with rainfall concentrated primarily during the summer months. Early summer (May–June) marks the peak temperatures before the onset of the rainy season. In Lake Pátzcuaro, mean annual temperature is 16.6°C, with mean annual precipitation of 987.4 mm, based on data from the period 1971–2000. Meanwhile, Lake Zirahuen has a mean annual temperature of 16.1°C and mean annual precipitation of 1,217 mm for the same period. During this timeframe, the maximum and minimum average temperatures are 25.1 and 8.1°C in Pátzcuaro, and 25.1 and 7.3°C in Zirahuen (INEGI, 2022).

Although human activities have significantly influenced the distribution and composition of vegetation in these basins, the natural vegetation is characterized by temperate forests. These forests consist mainly of pine (*Pinus*) and oak (*Quercus*), with fir (*Abies*) and pine dominating at higher elevations. The cloud forest, located at the summit of Cerro Zirahuen, spans altitudes ranging from 2300 to 2900 m (Torres-Rodríguez et al., 2012; INEGI, 2022). Agriculture, grasslands, scrub and secondary vegetation dominate lower altitudes. Emergent aquatic vegetation can be found around the lakeshores, covering extensive areas in Lake Pátzcuaro.

Gopar-Merino and Velazquez (2016) highlight the major impact of anthropogenic activity in reducing forest cover and biodiversity of Michoacán, which is home to >800 tree species. Today, temperate forests cover about 28% of the state, although modelling by these authors suggests a potential cover of nearly 43%. In recent decades, Michoacán, specifically the temperate forest area, has developed into Mexico's largest avocado-growing region (the Avocado Belt). This belt expanded by 43.5% between 1992 and 2017, resulting in significant deforestation (Arima et al., 2022). The Zirahuen Basin has seen a major expansion in avocado growing.

In the case of Lake Pátzcuaro, in addition to avocado plantations, extensive areas of commercial crops such as berries have been established (SIAP, 2023). This process has been aided by changes in land tenure, especially following the reform of Article 27 of the Constitution in 1992, which allowed for the buying and selling of collectively owned lands. In addition, urban growth and property development, especially in the vicinity of the town of Pátzcuaro, have led to changes in land use, further impacting the lake.

Historical human occupation and environmental dynamics

These basins have a long history of human occupation (Table 1). People settled there because of the access to water, fertile land and abundant fishing resources. Sedimentary evidence has uncovered a rich history of human interaction with the lakes and a long history of erosion, showcasing the active role of humans in shaping these landscapes (e.g. Bradbury, 2000; Lozano-Garcia, Caballero et al., 2010). Archaeological studies have also found evidence of terraces, chinampas (raised fields), irrigation systems and drainage systems within this region, suggesting the active of role humans in shaping and managing these landscapes (Fisher, 2000; Pollard, 2008; Williams, 2022).

In the Lake Pátzcuaro basin, the earliest indications of human presence date back to ~4000 cal a BP, evidenced by maize pollen found in lake cores (Bradbury, 2000). Palynological data from the Lake Zirahuen basin similarly reveal a rich cultural history, indicating human activity over the last 3500 years, although there is currently no archaeological confirmation of this (Torres-Rodriguez et al., 2012; Lozano-García, Vázquez-Castro et al., 2010). While archaeological studies in Zirahuen are limited, there is archaeological evidence of human settlements during the Postclassic period (after 900–1000 CE) (Pulido-Méndez et al., 1996).

In the Lake Pátzcuaro basin, the Middle Preclassic period (ca. 1000 BCE to 300 CE) is characterized by small village societies, marked by the development of the Chupícuaro culture (Table 1).

Figure 2. Gullying in (a) Pátzcuaro and (b) Zirahuen. (c) Influx of sediments into the lake margin at Zirahuen. (Photographs by SEM.). [Color figure can be viewed at wileyonlinelibrary.com]

Table 1. Timeline of major Mesoamerican periods, major cultural phases in the study region (Michoacán), and their expression in terms of settlement distributions and major centres. Population estimates are based on Gorenstein and Pollard (1983) and Pollard (2003, 2008).

Period	Cultures/phases	Expression
Colonial/modern (1521 onwards)	Independent Spanish Colonial	Capital = Pátzcuaro Initial population decline post-Conquest. Renewed growth from 18th century
Post Classic (900–1521/2 CE)	Purepecha/Tariacuri (from ca. 1350 CE) Urichu phase (900 to ca. 1350 CE)	Urban centres, centralized economies. Capital = Tzintzuntzan Large population (especially Purepecha period) Late Postclassic: ~80 000–100 000 people Middle Postclassic: ~48 000 people in the Pátzcuaro Basin
Classic (300–900 CE)	Loma Alta (early Classic)	Small settlements on islands or lake shores, e.g. Urichu, Erongaricuaro. Settlements expanded mid and late Classic
	Jaracuaro, Lupe/La Joya (mid Classic to early Post Classic)	Early Classic: ~5 000–8 000 people Late Classic: ~6 000–7 000 people.
Pre-Classic (ca. 1800 BCE to 300 CE)	Chupicuaro	Small villages

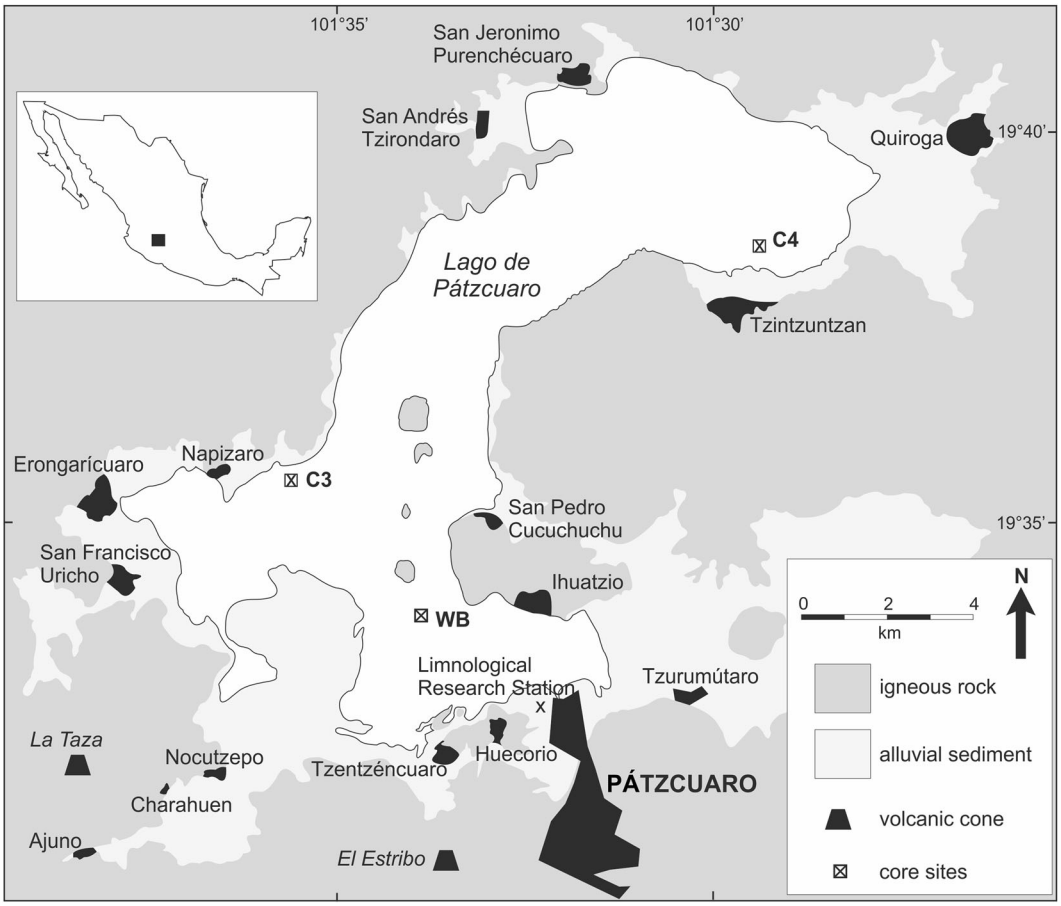

Figure 3. The Pátzcuaro basin showing key settlements and the locations of the Limnological Research Station and the Watts and Bradbury (WB), C4 and C3 cores.

The Late Preclassic and Early Classic (ca. 300–500 CE) saw the emergence of the Loma Alta tradition, signalling the rise of small-scale agrarian societies with social hierarchies. During this period, the population size is estimated to have been between 5000 and 8000 people. The implementation of irrigation as a form of agricultural intensification also originated during this period. During the Late Classic (ca. 800–900 CE), at least seven settlements were established in the southwest part of the Pátzcuaro basin, such as Uricho and Erongaricuaro (Fig. 3), with an estimated population of 6000–7000 people for the entire basin. Evidence suggests the continuous use of canal irrigation and wetland agriculture during this time. In the Early Postclassic (ca. 1000 CE), population growth persisted, reaching 12 000 people, accompanied by a decrease in lake levels, leading lacustrine settlements to relocate to new lake margins. Terraces and canals are also present during this period. In the Middle Postclassic, there was a significant population increase in the basin, with an estimated population of 48 000 people. As the lake continued to recede, many new sites were established on recently exposed islands and fertile lacustrine soils (Pollard, 2003, 2008).

The Late Postclassic period saw the rise of the P'urhépecha (Tarascan) state (1300–1522 CE), which covered the area of present-day Michoacán, including the Zirahuen Basin, as well as parts of Guanajuato, Guerrero and Jalisco. The P'urhépecha

state boasted a centralized economy, settlement, and political structures, urban centres, intensified landscapes and the highest population density of the Prehispanic era (Pollard, 1997; Table 1). The Lake Pátzcuaro basin stood at its epicentre, serving as a site of ceremonial, economic and social importance.

According to Pollard (2008), in the last decades of this period, lake levels rose again. O'Hara (1993) similarly characterizes this period as one of rising lake levels, associated with wetter climatic conditions. This led to the flooding of previously cultivable land, prompting widespread terracing to maximize food production amidst demographic growth (Fisher et al., 2003; Pollard, 2008). Gorenstein and Pollard (1983) suggest that the population of the Pátzcuaro basin was around 100 000 at the beginning of the 16th century (1522) but decreased significantly during the Early Hispanic period due to various factors, including diseases, conscription, emigration and widespread starvation (Warren, 1985). It has been argued that the P'urhépecha relied heavily on wood for construction and ceremonial bonfires, potentially leading to deforestation (O'Hara et al., 1993).

It would be expected that the intensity of human settlement in the pre-Hispanic period in the study catchments would be reflected in changes in land cover and, potentially, in erosion. The assessment of the intensity of this pre-Hispanic erosion is central to debates about the environmental impacts of indigenous land-use systems and provides the foundation for more recent assessments of environmental degradation and conservation policies.

Cultural and historical perspectives on erosion

The relationship between land-use systems and erosion has been examined from multiple perspectives. Endfield's (1997) study represents one of the pioneering efforts to investigate land degradation during the pre-Hispanic and colonial periods using historical sources. Focused on colonial Michoacán, Endfield's research delved into the environmental impacts of land-use changes, drawing insights from an array of historical sources, including colonial archives. Echoing previous studies (O'Hara et al., 1993), Endfield proposed that the post-Conquest era witnessed a 'recovery' of the landscape, marked by decreased rates of erosion. This recovery was attributed to indigenous depopulation and subsequent reduction in the intensity of land use.

In her analysis, Endfield highlighted that many landscape descriptions from the early colonial period suggested that the Spanish encountered pre-existing degradation in numerous locations, notably in the Pátzcuaro Basin. She suggested that these references may indicate either the immediate post-conquest impacts linked to grazing activity or the effects of pre-Hispanic land use (Endfield & O'Hara, 1999a). She also noted, however, that colonial landscape descriptions, both positive and negative, were shaped by their cultural, political and historical context of production. As such, they often served as instruments to persuade or conceal underlying intentions and agendas (Endfield & O'Hara, 1999b). Conversely, she noted that historical documents contained no references to land degradation in the Zirahuen Basin, suggesting that settlement and exploitation remained minimal in the area well into the 17th century (Endfield & O'Hara, 1999b). This idea of an undisturbed catchment has not been supported by the core studies (see below).

Regarding the immediate impacts of Spanish land-use systems in the region, substantial archival evidence revealed deforestation linked to the establishment of new towns and livestock-induced deforestation. Endfield, however, cautioned against attributing these changes solely to Spanish influence. If anything, she argued, Spanish land-use systems and the introduction of livestock contributed to a process of degradation that was already underway. Her research also revealed that the Spanish introduced conservative livestock-raising practices and regulations, although this did not always lead to conservation, as there was a tendency to maintain more livestock than allowed. Endfield also posited that the decrease in land-use intensity due to population decimation, especially in the initial century after the conquest, may have masked the environmental impact of the conquest, stressing the importance of considering the temporal dynamics of colonization.

According to Endfield (1997), it was not until the 18th century that changes in land tenure, population size and drought began to result in landscape instability and renewed land degradation in the Lake Pátzcuaro basin. Overall, she suggested that changes in land tenure under Spanish colonial administration and the intensity of land use were significant triggers of landscape instability, surpassing the influence of the land-use practices themselves. Barrera Bassols and Barrera de la Torre (2024) highlight that these colonial land-use practices were part of a broader process of 'disarticulation and territorial rearticulation'. They argue that the imposition of colonial land ownership structures disrupted the existing indigenous land-use systems, fundamentally restructuring the landscape to align with colonial economic interests. Significantly, these environmental histories echoed previous cultural and historical debates about Lake Pátzcuaro, regarding the character of indigenous land-use systems, a topic that will be further explored in the subsequent section.

In the case of Zirahuen, the basin witnessed a marked increase in Hispanic settlement and exploitation during the 18th century. By the mid-1700s, several large private estates, known as haciendas, were established to grow sugar, maize and wheat, as well as to raise cattle (Endfield & O'Hara 1999a). Some documents indicate environmental degradation in the basin around this time. By 1733, land in the southern part of the basin had been 'stripped of vegetation' (AGN Tierras 514 Expediente 3), while deforestation to the southwest of the lake had led to gullying (AGN Historia 73, Fojas 334–335). It appears that the steeper high ground surrounding the basin may have escaped deforestation. In 1789, Lago de Zirahuen was described as 'surrounded by high hills of pine' (AGN Historia 73, Fojas 391–392), and the view around Santa Clara was of 'mountains and hills populated with pine and some oak' (AGN Historia 73, Fojas 391–392).

Cultural debates on erosion during the mid-20th century

Recent history in these lake basins has been marked by concerns about erosion and land-use systems which have been prevalent since the early 20th century. These concerns arose in response to the widespread deforestation across Mexico, which was largely attributed to the introduction of railways and the expansion of the timber industry during the Porfiriato era (1877–1910), particularly in Michoacán (Boyer, 2012; Pérez Talavera, 2016). In this context, members of the Mexican Forestry Society as well as left-wing politicians and intellectuals emphasized the need to regulate natural resource exploitation, particularly of forests (Boyer, 2007; Boyer & Wakild, 2012).

During the early years of the Mexican Forester Society, from 1904 to 1910, its founder Miguel Angel de Quevedo put forward the idea that the loss of land cover was altering the

weather and causing erosion and floods. The question of land degradation also emerged as a key issue during the Mexican Revolution (1910–1920). In addition to the overexploitation of forest resources, the development of the timber industry led to the grabbing of communal forests through fraudulent contracts. As a result, revolutionaries believed that addressing land degradation required transforming property rights and land tenure systems.

This situation was particularly severe in Michoacán, where several logging companies had been established. Consequently, from the outset of the revolutionary movement, efforts were made to regulate forest exploitation. For instance, in 1911, following the overthrow of Porfirio Díaz's government, Michoacán's governor, Miguel Silva (1911–1913), proposed an amendment to the 1882 Michoacán Forestry Law, which was passed by the state congress one month later (Archivo Histórico del Poder Ejecutivo del Estado de Michoacán, Gobernación, Caja 2, Expediente 22). The reform allowed the suspension of logging operations that violated the law and stricter sanctions.

Michoacán's situation was central to discussions leading to the enactment of the 1917 Mexican Constitution. Revolutionary Francisco Múgica exposed logging companies' practices in Michoacán: alienating woodlands from communities, overexploiting the forest for large profits and underpaying locals. The Constituent Assembly agreed to review contracts and concessions made since 1876 that had led to the grabbing of natural resources and declared them invalid if found fraudulent. Timber companies in Michoacán had one month to submit their contracts for review, or face recission (INEHRM, 2016).

The 1917 Constitution addressed land ownership and natural resource protection through Article 27, which asserted national control over resources and imposed limits on private property. This coincided with growing interest among foresters in regulating resource exploitation, particularly of forests, leading to the 1926 Forestry Law. This law established the creation of protected areas and prohibited logging in upper basin areas to prevent erosion.

Advancing conservation through forest reserves and national parks

Forest conservation reached a new level with the establishment of the Forest, Hunting and Fishing Department (hereafter referred to as the Forestry Department) during President Lázaro Cárdenas' administration (1934–1940), appointing veteran forest conservationist Miguel Ángel de Quevedo as its director. The Forestry Department was founded with a strong conservationist ethos, tasked with managing natural resources, with forest protection as the cornerstone of its conservation programme (Quevedo, 1935a).

During this period, foresters were notably apprehensive about the potential consequences of land reform on forest conservation efforts. They firmly believed that the nation's wealth resided within its forests and that these could contribute to national progress if managed properly. Conversely, they viewed agriculture as the primary threat to forest conservation, which could precipitate national ruin. Consequently, the establishment of forest reserves and national parks was regarded as a strategic measure to safeguard their long-term preservation (Quevedo, 1935b).

Miguel Ángel de Quevedo, in particular, held unwavering convictions regarding the superiority of forestry over agriculture. He emphasized that the country's mountainous terrain favoured forestry as the most suitable land use, contrasting it with agriculture. Furthermore, he highlighted the long-term economic and environmental benefits associated with forestry, contrasting them with the perceived transient nature of agricultural activities (Quevedo, 1935c).

The allocation of forests as land reform parcels raised concerns about new agricultural land openings. Additionally, there were concerns about the overlap between national parks and forest reserves with newly granted ejidos and communal lands. Quevedo perceived this overlap as problematic, primarily due to his belief that indigenous and campesino communities lacked the education to use forest resources rationally. He also believed that forest and agriculture landscapes were incompatible, which conflicted with traditional agroforestry systems characterized by overlapping management systems, such as those seen in slash-and-burn agriculture. The establishment of national parks, while not leading to the forced eviction of indigenous communities from their territories, did restrict agriculture and forest use, encouraging a recreational use instead.

Despite conservationists disregarding indigenous management practices, they also considered that with careful monitoring and education, the rational exploitation of forests could help improve the economy of the rural population. In this context, the Forestry Department aimed to transform management practices from traditional to modern and scientific, aligning with the post-revolutionary cultural initiative to modernize rural and indigenous communities. Given its strong confidence in science, the Forestry Department also believed that science could improve nature, making it more productive while ensuring its conservation.

Protecting the forest, protecting the lake

The emphasis of the Forestry Department conservation programme on the protection of forests rested on the idea that in a mountainous country like Mexico, protecting forests meant preventing the adverse effects of erosion and protecting soils, bodies of water and fishery resources. Following a basin management approach, the conservation programme established a link between the protection of forests and water bodies with the protection of wildlife and soil conservation. This approach enabled the regulation of activities occurring in different parts of the catchment, such as agriculture, forestry and fishing (Quevedo, 1935b).

The Forestry Department considered the forests of central Mexico as the most threatened due to these areas' high population densities and demands for land redistribution. They reported that the situation was particularly critical in the states of México, Morelos and Michoacán, advocating for the establishment of the largest forest reserves in these areas. The lakes of Pátzcuaro and Zirahuén were perceived as highly endangered and requiring immediate protection. The consequences of erosion were perceived both in environmental and aesthetic terms since it was affecting the scenic beauty of lakes and their condition as habitats (Quevedo, 1935b, 1935d, 1936a).

Government efforts focused primarily on Lake Pátzcuaro, partly due to its cultural and historical significance. On 7 January 1936, authorities declared the Lake Pátzcuaro basin a 'forest hydrological reserve' to protect against land-use changes and erosion. The Lake Pátzcuaro forest reserve also aimed to maintain the lake's condition as a habitat for fish species. This last argument was complemented by the idea of setting up an aquacultural and limnological monitoring station (see below). The decree prohibited opening new agricultural lands if it posed any risk to the existing forest cover and the introduction of livestock in areas subject to reforestation or natural regrowth. It also established compulsory reforestation

for owners whose land was denuded or located on a slope (DOF, 1936).

The decree further stipulated that residents within the reserve could continue using their forests, provided they were within their ejidos (land reform plots) and operated as part of a cooperative (DOF, 1936). Significantly, the department regarded indigenous agricultural practices, especially farming on slopes and slash-and-burn agriculture, as detrimental to forest conservation efforts and conducive to land degradation. Therefore, through the establishment of the forest reserve, the Forestry Department aimed to transform indigenous management practices.

Perceptions of the interplay between deforestation, erosion, and fisheries

The issue of erosion figured prominently in discussions concerning fisheries, particularly in Lake Pátzcuaro. These discussions were triggered by the decline of the endemic whitefish (*Chirostoma estor*) in Lake Pátzcuaro that the Forestry Department wanted to propagate to other reservoirs outside its natural distribution area. These debates around erosion were deeply intertwined with value judgments regarding indigenous management practices (fishing and agriculture), which were perceived to impact the ecosystem dynamics of the lake (Aguilera Lara, 2022).

The protection and propagation of the whitefish held profound social and cultural implications beyond ecological concerns due to its ties with the traditional lifestyles of indigenous people and Michoacán's pre-Hispanic heritage. To address the declining whitefish populations, the Forestry Department proposed a limnological research station in Pátzcuaro. This station would monitor lake conditions and develop reproduction techniques for whitefish and other economically valuable species. The collaboration of two Japanese experts, Yoshiichi Matsui and Toshie Yamashita, from the 'Piscicultural Branch of the Imperial Fisheries Experimental Station', further influenced these efforts.

During their first research trip to the lakes of Pátzcuaro and Zirahuen in April 1936, the team set out to assess the productive potential of these lakes and investigate the causes behind the decline of the whitefish population (Quevedo, 1936b). One outcome was the first characterization of these lakes, serving as a benchmark for their current status. In the case of Pátzcuaro, they characterized the lake as shallow, with a maximum depth of 14 m, assigning a water colour rating of 9 on the Forel scale and transparency of 2.2–2.4 m – a notable contrast to the 30-cm visibility recorded in 2010 (Sánchez-Chávez et al., 2011). Due to the high abundance of plankton, the most prevalent planktonic copepod, they also considered the lake optimal for the propagation of fish from temperate waters, especially juveniles, positioning it as having great aquaculture potential (Matsui and Yamashita, 1936).

In the case of Zirahuen, while no limnological data were collected, they described the lake as deep and cold, ideal for Salmonidae fish propagation. In addition, the report from the head of the fisheries service described the complete lack of vegetation on the surrounding hillsides and emphasized the need for immediate reforestation to prevent erosion (Berriozabal, 1936). A photograph illustrating the report (Fig. 4) captures this situation. This perception of the lake's status contrasts sharply with future representations of Lake Zirahuen basin as undisturbed. Unlike Pátzcuaro, no suggestions were made regarding the causes of deforestation or erosion. Ideas about the causes of the observed decline in whitefish initially focused on overfishing by indigenous fishers, but Matsui later revised this view and suggested other factors, including deforestation and climate change (Valle, 1938).

Echoing sentiments within the Forestry Department, Matsui attributed the loss of local forests to agricultural activities, resulting in erosion, altered weather patterns and the degradation of Lake Pátzcuaro's habitat. He also suggested that deforestation-induced climate fluctuations could lead to lake-level fluctuations and be a factor in the decline of whitefish populations. Matsui emphasized the need for extensive reforestation to stabilize water levels and increase fish abundance (Valle, 1938).

During the subsequent decade, early anthropological and cultural geography studies highlighted deforestation and erosion as pressing issues affecting the Lake Pátzcuaro basin (Foster, 1948; West, 1948; Brand, 1951). Despite existing forest regulations, West (1948) criticised most forest exploitation

Figure 4. Photograph showing deforestation of the hillsides of Lake Zirahuen (far side of lake). Source: Berriozabal (1936).

practices as destructive, echoing the sentiments of forest conservationists in the 1930s.

The Pátzcuaro Limnological Station

The inauguration of the Pátzcuaro Limnological Station in 1938 signalled a significant shift in the examination of the connection between the upper catchment and the lake, as this relationship would now be scrutinized through the lens of limnology. The station's activities included continuous monitoring of meteorological data and physical–chemical water parameters, lake level measurements, plankton, the study of fish species and experimentation on fish farming. Importantly, while its primary research focus remained on Pátzcuaro, the limnological station also conducted research in other water bodies both within and beyond the region, including Zirahuen.

The Pátzcuaro Limnological Station provided the first characterization of Zirahuen. The maximum depth recorded in 1942 was 46 m, with the water colour rating at 7 on the Forel scale. The lake's slopes were predominantly described as covered by pine and oak forests, with modest erosion and some gully formation in the early stages of evolution (De Buen, 1943). This description stands in contrast to observations made by the forestry department in 1936, which noted a complete lack of vegetation (see above).

The research at the limnological station led to various propositions about Lake Pátzcuaro's origin and future. Based on the similarity of their icthyofauna, it was suggested that the lakes of Zirahuen, Pátzcuaro and Cuitzeo were once tributaries of the Lerma river (De Buen 1943). Successive volcanic episodes isolated the lake basins, with Zirahuen and Pátzcuaro separating first, followed by Cuitzeo. There is, however, currently no evidence to support this hypothesis, as geological data suggest a relatively recent origin for Zirahuen (Ortega et al., 2010; Osorio-Ocampo et al., 2018). Alternatively, Bernal-Brooks (1998) suggested a former connection with the Balsas drainage system to the south as more plausible.

De Buen (1943) also proposed a theory on the evolution of Michoacán lakes. According to this, the lakes of Michoacán were evolving towards a final demise, becoming valleys that were once lakes. Based on the morphology of the Lake Pátzcuaro basin, he suggested that the lake was deeper in the past and had a smaller surface area. However, he argued that erosion over time had led to a reduction in depth, accompanied by a loss of transparency in its waters (De Buen, 1941). De Buen (1943) also observed a recession of the lake's waters, particularly notable in Chapultepec and Quiroga, where land has become available for agriculture. Furthermore, he observed localized soil erosion in Ihuatzio, southeast of the lake (Fig. 3). According to De Buen (1943), Zirahuen was heading towards the same situation as Pátzcuaro. He observed that deforestation by fire and logging would shorten the geological evolution of Zirahuen, ageing rapidly and losing its transparent and deep waters.

West (1948) reiterated previous evaluations of Zirahuen as a comparatively deep lake with consistent water levels and Pátzcuaro as a shallow lake with fluctuating water levels. Referencing data from the limnological station, he noted that since 1939, the water level of Lake Pátzcuaro had decreased by ~4 feet (1.2 m).

As De Buen's theory gained currency, it triggered interest in the reconstruction of the environmental past of these lakes, especially Lake Pátzcuaro. In 1941, American palaeolimnologist Edward S. Deevey obtained the first sediment core from Lake Pátzcuaro (6.2 m in length), with the assistance of the Pátzcuaro Limnological Station.

Insights from a palaeoenvironmental perspective

The earliest published palaeoenvironmental studies of Lake Pátzcuaro primarily examined the potential of basin sediments as a record of climate change (Deevey, 1944). Further studies on the Deevey core revealed *Zea mays* pollen (Hutchinson et al., 1956), indicating that agriculture had been practised in the basin for a long time, anticipating future debates on the impact of prehsipanic agriculture. These studies, lacking dating control, were unable to explore to what extent sediment accumulation rates had changed and hence make any link to erosion. It was not until the application of radiocarbon dating and other dating techniques, such as tephrochronology, that the questions of timing and erosion rates came into sharper focus.

Watts and Bradbury (1982) presented a record from a core from the southern part of Lake Pátzcuaro extending back into the Pleistocene (ca. 44 000 BP, 48 000 cal a BP). This work, while initially focused on climate change, revealed evidence of human activity dating back to ~3600 BP (ca. 4000 cal a BP). The available dates showed clear evidence for very high rates of sediment accumulation from the onset of this disturbance, but this was not explored in the paper. No dates were available from the upper 2 m of the core.

From the late 1980s, a series of studies began focusing specifically on the basin's erosion history. Initial investigations, based on surface exposures, later expanded to include short cores from across the lake. These studies revealed two distinct episodes of environmental degradation triggered by the widespread adoption of maize cultivation during the Preclassic period and the late Postclassic–Hispanic period.

The most comprehensive study of basin-wide erosion remains that of O'Hara et al. (1993), largely based on 20 relatively short (<3 m) cores taken from across the lake and resampling of the Watts and Bradbury (1982) core. Various methods, such as magnetic susceptibility, sediment chemistry and bulk density, were used to identify erosional events, with a radiocarbon chronology. O'Hara et al. (1993) identified three periods of accelerated erosion: one coinciding with the expansion of maize cultivation, between 3600 and 3000 BP (3850–3150 cal a BP), another during the late Preclassic/early Classic period, between 2500 and 1200 BP (2600–1 cal a BP, and a third during the Postclassic, 850 BP (750 cal a BP) and the present, shortly after the arrival of the P'urhépecha. The last period of erosion was notably widespread, especially in the north, and was attributed to extensive forest clearance (see above). The annual average rate of sediment accumulation during the second and third periods was estimated to be 10 300 and 29 000 t respectively.

O'Hara et al.'s (1993) findings influenced Bradbury's (2000) subsequent study into erosion patterns in the period after 3600 cal a BP, noting the deposition of iron-rich clay and abundant phytoliths between 1800 and 1200 cal a BP. The onset of significant nutrient loading in the lake was suggested to have commenced around 800 cal a BP, coinciding with the flourishing of the P'urhépecha State when the Pátzcuaro basin became the political, administrative and ceremonial centre.

O'Hara et al. (1993) also examined the relationship between erosion and the Spanish conquest, finding no evidence to suggest that the arrival of the Spanish and their farming techniques had any discernible impact on increasing erosion rates. They proposed that the demographic collapse resulting from diseases introduced by the Spanish around 1541 CE led to a reduction in land-use intensity and forest regeneration, temporarily stabilizing erosion rates within the catchment. This view was subsequently confirmed by Endfield's historical research described above.

An alternative view on erosion history was presented by Fisher et al. (2003), focusing on the relationship between land

management practices, population density and erosion patterns. Specifically, they analysed the vulnerability of land management systems, such as terrace systems, to sharp population decline. Their study was concentrated solely on the southwest corner of the basin, using a large number of exposures, including wells, trenches and auger cores. They suggested that before the arrival of Spanish settlers, erosion was not at a landscape scale, but rather associated with particular settlements. In contrast, during the Hispanic period, the scale of erosion changed due to the wholesale abandonment of previous intensive land management systems, exacerbated by new crops and practices, and a period of high rainfall. In a later paper, Fisher (2005) emphasized that agriculture per se may not be responsible for large-scale erosion if the environment is properly managed. In Pátzcuaro, this may have allowed a rapidly growing population during the early Postclassic period (around 900 CE) to prevent widespread degradation, but a very diminished population in the early Hispanic period to see widespread erosion. Unfortunately, dating control of the most recent sediments in all published studies is inadequate to shed light on the fine detail of events during the Hispanic period, but an increase in nutrient loading in the lake is evident.

Subsequent research by Metcalfe et al. (2007) confirmed O'Hara's (1993) original findings about the spatial scale of early disturbance and an absence of evidence indicating increased erosion during the Hispanic period. Despite the clear evidence of erosion in the modern catchment (e.g. gullying, Fig. 2a), it could be that the whole system is now supply-limited. A detailed analysis of the magnetic properties of the Pátzcuaro sediments from core C4 in the northern part of the lake indicates that over the past 3000 years, an increasing proportion of the sediment has come from the subsoil and bedrock (Figs. 3 and 5; Metcalfe et al., 2007). The interaction of climate and erosion, noted earlier by Bridgwater et al. (1999), is also drawn out in this later study, with some periods of catchment stability related to dry periods.

Although erosion in Lake Pátzcuaro has been studied for a long time, research on the nearby Lake Zirahuen, which was part of the same P'urhépecha empire, only began in the early 2000s. At the time, there was little archaeological evidence of settlement in this basin and the lake itself seemed relatively undisturbed. Early research challenged these assumptions. The initial investigations focused on the past millennium and used age control from radiocarbon, tephrochronology (ash layers of known age from the volcanoes Jorullo and Paricutin) and ^{210}Pb (Davies et al., 2004). This study indicated an early phase of erosion between about 1100 and 1500 CE (Postclassic), although with no archaeological evidence for specific settlements during this period. Catchment stability in the early Colonial Period (ca. 1550–1750) was recorded, followed by renewed erosion and evidence of the impact of nearby copper smelting. This was also linked to the population increase referred to in historical documents. Very rapid change was indicated over the last 20 years of the record (up to 1998), including influxes of reddish silt from the basin slopes (see Fig. 2c) and a rapid increase in nutrient status.

The collection of longer cores from this lake has now enabled more direct comparisons with the erosion history of Pátzcuaro. Ortega et al. (2010) published a record spanning ~17 000 years from near the northern shore of the lake, although the sequence had a hiatus between ~12 000 and 7200 cal a BP. A complete record was obtained from a core retrieved from the central part of the lake (Lozano-Garcia et al., 2013).

Both core sequences showed clear evidence of human impact in the lake during the Holocene (4300–1400 cal a BP),

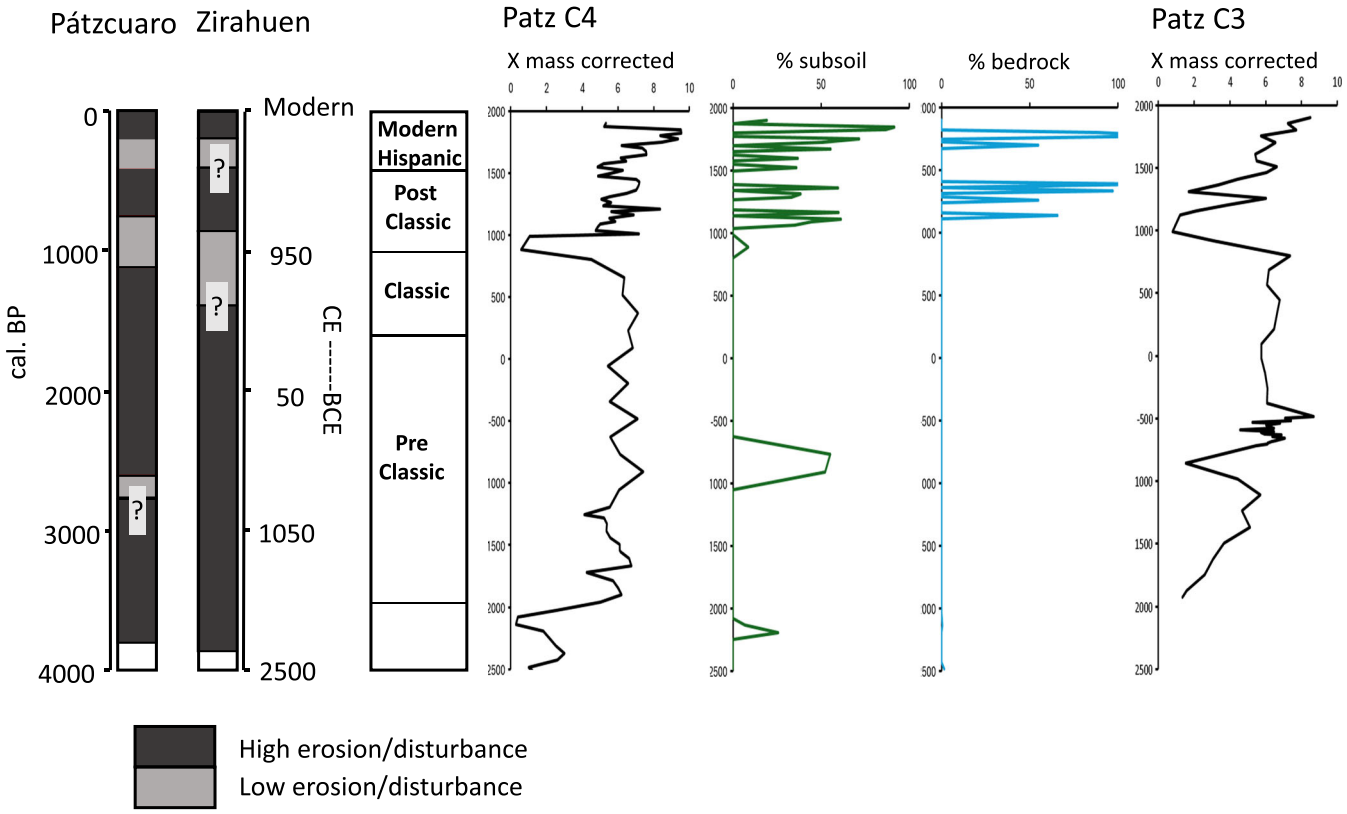

Figure 5. Periods of erosion and stability in Pátzcuaro and Zirahuen based on published sources and compared with a timeline of major cultural periods. Sources: Watts and Bradbury (1982), Street-Perrott et al. (1989), O'Hara et al. (1993), Bradbury (2000), Metcalfe et al. (2007) (Pátzcuaro); Davies et al. (2004), Ortega et al. (2010), Torres-Rodriquez et al. (2012), Lozano-Garcia et al. (2013) (Zirahuen). Mineral magnetic data from cores C4 and C3 from Patzcuaro show changing inputs of erosion over time and the probable changes in the nature of source material, particularly in the Post Classic period (data from Metcalfe et al., 2007, core locations on Fig. 3). [Color figure can be viewed at wileyonlinelibrary.com]

with increased erosion associated with maize pollen (3500 cal a BP), increased charcoal and more herbaceous pollen (Ortega et al., 2010; Torres-Rodriguez et al., 2012; Lozano-García et al., 2013). This signal, particularly evident during the late Classic P'urhépecha period, is clearer in the nearshore core than in the deepwater core. The authors report the strongest impact signal in the P'urhépecha period, after 1050 CE. In their nearshore core, however, this high erosion continues into the early colonial period (cf. Davies et al., 2004). As in Pátzcuaro, there are indications that erosion is not simply a product of human activity; it is also influenced by climate. Ortega et al. (2010) note decreased erosion and a drier climate in the middle to late Classic period (ca. 550–1050 CE), a trend also observed in Pátzcuaro and Zacapu to the north (Metcalfe, 1995). Drying in the late Classic is now widely documented across the lakes of central Mexico (e.g. Metcalfe & Davies, 2007; Bhattacharya et al., 2015; Wogau et al., 2019; Ortega-Guerrero et al., 2021; Caballero et al., 2023).

These core studies highlight the longevity of soil erosion as a process within the lake basins of Michoacan; the timing of erosion/disturbance episodes in Pátzcuaro and Zirahuen (Fig. 5) show marked similarities. These patterns occur more widely across Mesoamerica. They confirm that vegetation change, associated with agriculture (specifically maize cultivation), has been closely associated with changes in erosion, although other factors do come into play. This long-term history of environmental degradation provides the context in which conservation policies have been developed, including Quevado's attitudes to indigenous management practices, which can be understood most effectively through linking both scientific and cultural–historical perspectives.

Discussion and conclusions

The volcanic soils of the lake basins of upland Michoacan are known for both their fertility and their erodability. The naturally predominant temperate forests have been cleared, with varying intensities, over the late Holocene, initially for maize cultivation, then cattle ranching and most recently avocado growing. In addition, timber has historically been used for building, furniture making and ceremonial purposes, and population growth has also led to forest clearance. Today, other significant drivers of this process include organized crime, urban expansion and property development.

The resulting erosion manifests visibly through gullying and less visibly through loss of fertile topsoil, accumulation of sediments on lower slopes, and increasing nutrient and sediment loads entering lakes. These effects and their link to pre-Hispanic, indigenous and colonial management practices have been the focus of debates across a range of disciplines and timescales. Understanding this erosion from a long-term perspective underscores a history of continuous land use and landscape transformation.

In this paper, we have explored these debates in the context of the Pátzcuaro and Zirahuen basins. The former is unfortunately well known for its poor environmental status, while the latter has been perceived as relatively 'pristine' until recent decades. Interests in conservation, integrating the protection of both forests and lakes, can be traced through the establishment of government departments and agencies, the instigation of limnological monitoring and the study of lake sediments to explore long-term catchment histories. Together with the use of insights from historical documents and ethnographic studies, these approaches have highlighted the complex interplay between the natural environment and human society, especially the interactions between soil erosion, climate, land-use practices, land tenure and socio-political systems.

Integrating the different approaches can be quite challenging. In the case of Pátzcuaro, we have a reasonable archaeological record, good historical information and long-term (if not continuous) limnological monitoring. The lake itself, however, is shallow and well mixed, so the sediment record has low inherent resolution and obtaining highly resolved chronologies is problematic. The impacts of both volcanism and tectonism on the lake sediments are also evident (e.g. Telford et al., 2004; Israde-Alcántara et al., 2005). As a result, linking historical events to the sediment record has been difficult. In contrast, Zirahuen has little/no archaeological historical information and limnological data collection (still not routine) is quite recent. The lake itself is deep and poorly mixed (mixing only occurring in the winter months) and therefore suitable for high-resolution sediment records. For example, the sediments have preserved tephras from the dated eruptions of Jorullo and Paricutin, which facilitates comparison with both historical and instrumental records. Recent eutrophication of the lake shown by monitoring of the lake via the use of satellite imagery has been shown in core records to date back to the 1980s.

Forest conservation and the policies around this have reflected changing attitudes and concerns, including ideas about the relative merits of agriculture and forestry, the conservation value of indigenous management practices and the relationship of catchment and lake. The recent Law of Forest Development of Michoacan (Ley de Desarollo Forestal del Estado de Michoacan, 2016) stems from a watershed management perspective that can be traced back to the first half of the 20th century. The objectives of this law align with broader conservation efforts aimed at mitigating erosion, enhancing biodiversity and safeguarding water resources, but also emphasize the rights of indigenous communities to prioritize the sustainable use and enjoyment of forest resources within their territories.

Forest clearance remains a key driver of soil erosion, although rates of deforestation in Michoacan apparently slowed between 2007 and 2014, in spite of the continued expansion of the Avocado Belt (Mas et al., 2017). This slowing in forest loss was attributed to conservation initiatives such as Pro-Arbol (Pro-Tree) and payment for environmental services, but also to population migration from rural to urban areas. Michoacan remains a predominantly rural state (>97% in 2020), but its population growth has slowed dramatically since the late 1990s, being only 0.9% for the period 2010–2020. Out-migration, some driven by security concerns, has been identified as an issue for the state.

The question of how far traditional/indigenous land-use practices, over different timescales, might impact conservation efforts remains. Barrera-Bassols and Zinck (2003) in a study of a P'urhépecha community in the Pátzcuaro basin suggest that indigenous knowledge can protect the environment, but note that this traditional knowledge is being lost. In their study community, the number of farmers had declined. Some farmers switched to handicrafts and furniture making, which had the effect of reducing forest cover in the community by 14% between 1986 and 1992. These economic changes were associated with the increasing commercialization of agriculture (some associated with NAFTA), out-migration and a move from collectivism to individualism.

The current study has highlighted the multiple drivers of forest clearance and erosion, and illustrated both the visible and less visible impacts of that erosion, themselves reducing the biodiversity, economic and aesthetic value of these lakes and their catchments. How pre-Hispanic indigenous populations

attempted to control erosion is hard to ascertain, but in both basins there is clear evidence that forest clearance (for whatever reason) led to a significant increase in erosion. In the immediate post-Conquest period, this erosion was initially reduced in response to a dramatic decrease in population, but then resumed although not at significantly higher levels than previously. In the 20th century, concerns about deforestation and more focus on broader issues of conservation led to more direct regulatory action through government departments and agencies, particularly the Forestry Department. It also resulted in the establishment of limnological monitoring in Patzcuaro as the connections between deforestation, erosion and fisheries potential were recognized. The possible links to climate were also more clearly articulated. Initially critical views of indigenous people and their practices have recently been replaced by more recognition of the potential value of traditional knowledge. The importance of this local knowledge in conserving agrobiodiversity and associated landscapes has been highlighted by other researchers (Mapes et al., 1994; Astier and Barrera Bassols, 2006). The importance of effective management, raised by Fisher (2005), remains irrespective of its basis. Bernal Brooks (2021) further emphasizes the necessity of culturally grounded actions to address environmental issues effectively in the Patzcuaro basin, especially in response to failed conservation practices that overlooked these aspects and to mitigate biases in knowledge. Overall, this emphasizes that understanding the drivers of soil erosion really does require an holistic approach, with climate change threatening to affect multiple elements of an already complex system.

Acknowledgements. SEM would like to acknowledge the support of the Leverhulme Trust (F158/BL), NERC (Radiocarbon awards 979.0402, 877.08 and file 14.36) and AHRC (B/RG/AN6489/APN10651). JAL thanks CONACYT for the doctoral scholarship (622446) that made the collection of some data presented in this paper possible. We would like to acknowledge the contributions of discussions about these basins with many collaborators including Prof. Georgina Endfield (University of Liverpool), Dr Arturo Chacon Torres and Dr Isabel Israde Alcantara (UMSNH), Dr Socorro Lozano Garcia (UNAM), Prof. Sarah Davies (Aberystwyth University), Prof. Sarah O'Hara and Prof. David Matless (University of Nottingham), Dr Anthony Newton (University of Edinburgh) and the late Dr J. Platt Bradbury.

Data Availability Statements

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Abbreviations. AGN, Archivo General de la Nación (National General Archive - Mexico); BCE, Before Common Era; BP, Before Present; CENAPRED, Centro Nacional de Prevención de Desastres (National Centre for Disaster Prevention - Mexico); DOF, Diario Oficial de la Federación (Official Gazette of the Federation - Mexico); INEGI, Instituto Nacional de Estadística y Geografía (National Institute of Statistics and Geography - Mexico); NAFTA, North American Free Trade Agreement; SAGARPA, Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación (Ministry of Agriculture, Livestock, Rural Development, Fisheries and Food - Mexico); SIAP, Servicio de Información Agroalimentaria y Pesquera (Agricultural and Fisheries Information Service - Mexico).

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