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**SHORT COMMUNICATION**

# Potential for carbon sequestration in severely degraded temperate climate sites: Acrisol and Andosol gullies in Mexico

Michelle Carrillo-Castañeda[1], Aislinn A. Jiménez-Belmán[2], Mariela Gómez-Romero[2,3], Felipe García-Oliva[4] and Roberto Lindig-Cisneros[4]

*[1]Facultad de Ciencias, Universidad Nacional Autónoma de México, (UNAM), Ciudad Universitaria, Alcaldía Coyoacán, Ciudad de México, 04510 Mexico. [2]Facultad de Biología, Universidad Michoacana de San Nicolás de Hidalgo (UMSNH), Morelia, Michoacán, 58030 Mexico. [3]Cátedra, Consejo Nacional de Ciencia y Tecnología (CONACyT), Ciudad de México, 03940 Mexico. [4]Instituto de Investigaciones en Ecosistemas y Sustentabilidad, Universidad Nacional Autónoma de México (UNAM), Morelia, Michoacán, 58190 Mexico*

***Correspondence** should be addressed to Roberto Lindig-Cisneros: rlindig@iies.unam.mx

## Abstract

*Aim of study*: We assessed potential carbon (C) sequestration in gullies formed in Acrisols and Andosols, on the basis of long-term field restoration trials and GIS analysis.

*Area of study*: Two field trials in Michocán, Mexico, restored with *Pinus pseudostrobus, Pinus greggii* and *Pinus devoniana* in 2005 and 2009.

*Material and methods*: Soil C content was analyzed from field samples, and C content of aerial tree biomass of the three *Pinus* species was estimated by means of allometric equations. The potential restoration area was calculated with a GIS using available layers from the INEGI (Mexican National Institute for Geography and Statistics).

*Main results*: The spatial analysis showed that 1.83% of the Mexican territory are Acrisols and 1.18% are Andosols. From which, 40.87% of Acrisols and 42% of Andosols are eroded. The area with gullies was 2810 km² for both groups of soils within the elevational range of conifer forests in Mexico. C content at the two restored sites was on average of 1.27 t/ha. Soil C content in a 30-cm depth profile was 4.25 t/ha. The potential C sequestration for an average period of 13 years for an area of 2810 km² was 3.947 megatons of C (MtC). A total of four states – Michoacán, Chiapas, Oaxaca, and Puebla – concentrate 89% of the possible capture.

*Research highlights*: Severely degraded sites where gullying is dominant have a high potential for C sequestration once erosion has been controlled and plant cover has been restored.

**Additional keywords:** ecological restoration; climate change; conifer, mitigation.

**Abbreviations used:** INEGI (Mexican National Institute for Geography and Statistics).

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# Introduction

Worldwide climate change is having severe consequences in the biosphere, and present concentration of atmospheric carbon dioxide has driven global surface temperature up nearly one degree centigrade (IPCC, 2021). Climate change forecasts for Mexico contemplate an increase in average annual temperature of 1.5°C by 2030, 2.7°C by 2060 and 3.7° by 2090, when compared to weather records taken in the 1961-1990 period (Sáenz-Romero et al., 2010). The rising detrimental consequences that climate change will have on Mexico's temperate forests are only one of the many repercussions it will have on the country. As temperatures increase and rainfall decreases, drier conditions will result, thus causing loss of climatic habitat across Mexican ecosystems (Sáenz-Romero et al., 2010). These changes in the climatic niche are consistent with climatic habitat models for individual species, including coniferous such as: *Pinus hartwegii* Lindl., *Abies religiosa* (Kunth) Schltdl. & Cham., *Pinus pseudostrobus* Lindl., *Pinus devoniana* Lindl., and *Pinus oocarpa* Schiede ex Schltdl. (Gómez-Pineda et al., 2020).

Soil erosion is one of the major environmental problems worldwide, and it has been identified as the main factor in soil degradation (Zhou et al., 2021). In severely eroded soils microbiota is disrupted or suffers considerable loss, humidity retention is diminished, and soil structure is modified; in the absence of a protective plant cover, rain falls directly on the soil, leading to the disintegration of unconsolidated soil material and triggering sedimentation when soil particles are dispersed by runoff (Pérez-Nieto et al., 2012), and contributing to global warming by freeing carbon dioxide into the atmosphere (Lal, 2004). Iron-rich soils are sensitive and prone to degradation, especially when plant cover has been lost. In this scenario such soils present high erosion rates and the formation of gullies (Lindig-Cisneros et al., 2019). Gullies is a form of advanced soil erosion caused by water runoff when water flows into channels or rills after intense rainfall. Andosol and Acrisol in humid climates follow an evolutionary pathway that start with the former and ends with the latter (Solleiro-Rebolledo et al., 2019).

Restoration of degraded soils has a positive effect on ecosystems, the quality of water bodies and C sequestration, thus contributing to counteract the impact of climate change. Soil restoration management practices allow annual C accumulations of 50 to a 1000 kg/ha (Lal, 2004). There are large tracts of land worldwide where soil loss has been severe, such as areas dominated by gullies, where soil fertility for agricultural use cannot be restored but that can be restored for C sequestration and prevention of further catchment degradation.

The aim of this study was to assess potential C sequestration in Acrisol and Andosol-dominated sites with gullies in Mexico, on the basis of GIS analysis and field restoration trials which began fifteen and eleven years ago. Sites with Andosol and Acrisol were selected due to the evolutionary link between these two types of soil. The potential sites were chosen due to the presence of gullies and elevation (between 1500 and 3500 m a.s.l.). This elevation range correspond to that of most *Pinus* species recognized for Mexico: *P. leiophylla*, *P. herrerae*, *P. hartwegii*, *P. pseudostrobus*, *P. montezumae*, *P. devoniana*, *P. oocarpa*, *P. teocote,* and *P. greggii* (Farjon et al., 1997). Moreover, there are other species, such as *P. caribea*, currently growing at elevations below 1500 m a.s.l. which may be made to migrate to higher elevation in the future as a management option.

# Material and methods

## Study sites

In a gully-dominated area that had previously undergone restoration trials in 2005 and 2009, we evaluated the sequestration of C in the soil and plant biomass (Gómez-Romero et al., 2012; 2013). The species we used in these restoration trials were *P. pseudostrobus, P. greggii* and *P. devoniana* and were planted at *Las Huertitas* in the Atécuaro *ejido* (19° 33' 05'' N and 101° 05' 07'' W, 2 275 m a.s.l.), municipality of Morelia, Michoacán, Mexico. The site has been characterized in terms of soil characteristics that relate whit erosion processes by Duvert et al. (2010), who determined that the Huertitas subchachment has a mean slope of 18% and shows gullies in 6% of its area. Because of the climate in the area (subhumid temperate climate with summer rains, an annual average temperature of 13.8°C, and an annual average precipitation of 1000 mm) most of the subcachment discharge occurs during the wet season (10-30 L $s^{-1}$). Other studies in gullies from the same area indicated that soils are deep and no rocks are exposed even un gullies as deep as 4 m (Bravo-Espinosa et al., 2010). When the restoration trials were established plant cover in the gullies was 0%, 15 and 11 years after that, tree canopy cover ranged from 80% to 100% (Fig. 1).

A study in the subcachment where the restoration trials of the present study were carried out (the Huertitas subchachment in Atecuaro, Michoacán, Mexico), made by Sánchez Morales (2008), found that Andosol has a loose texture, apparent densities below 0.9 g $cm^{-3}$ and a porosity of 69%; in contrast Acrisol has a clay texture, and apparent density of 1.25 g $cm^{-3}$, and a porosity of 52%. When these soils degrade, their high iron content, low microorganism activity, scarce organic matter and lack of available phosphorus and nitrogen become significant barriers to plant establishment and development and hinder plant successional processes in sensitive ecosystems or sites which have been subject to human disturbance (Oliet et al., 2005).

## Assessment of carbon sequestration

In the year 2020, the restored areas were divided into 10 plots and soil samples were taken from two randomly


**Figure 1**. Restoration trials when established in 2005 (A) and 2009 (C) and in the year 2020 (B and D). The amount of tree canopy cover ranged from 80% to 100%.

selected points in each plot. Leaf litter was removed from the surface before sampling. Since a layer of cemented material known as *tepetate* was discovered, every sample was taken up to 30 cm deep within a 10 × 10 cm square section core. Each sample was then divided into three 10 cm sections. Also, 3 samples were taken from gullies outside the restored area following the same procedure. We quantified C concentration in soil samples by means of combustion and coulorimetric detection (Huffman, 1997) with a total C analyzer (UIC-COULOMETRICS mod. 50120). Biomass and C content of aerial tree biomass was estimated by means of allometric equations (Velasco et al., 2012), diameter and height of 495 individuals were measured for this end.

### Estimation of potential restoration area

The potential restoration area was calculated with a GIS using available layers from the INEGI (Mexican National Institute for Geography and Statistics). The layers were processed to obtain polygons that complied with the following criteria: a) areas corresponding to Acrisols or Andosols; b) gully-dominated sites; and c) elevation from 1500 to 3500 m a.s.l.

The INEGI layers used were the following:

a) Edaphic data vector layer, scale 1:1,000,000 (INEGI, 2005). From this layer, the polygons corresponding to Andosols and Acrisols were obtained.

b) Erosion data layer, scale 1:250,000 Series 1 (INEGI, 2014). The gully-dominated polygons were obtained from this layer.

c) Elevation data was obtained from the topographic vector layer, scale 1:4,000,000 (INEGI, 2001), to obtain the polygons with elevations from 1500 to 3500 m a.s.l. A geometric correction was applied to all layers and the Conic Lambert Projections were used. All geoprocessing was carried out with QGIS 3.20.1 (QGIS, 2022).

## Results and discussion

Based on the layers used, we performed a geographical analysis of the 1,960,189 km$^2$ continental area of Mexico, and the results indicated that water erosion occurs in around 40% of Acrisols and 42% in Andosols. At the national level, 36,034 km$^2$ (1.83%) are Acrisols and 23,306 km$^2$ (1.18%) are Andosols. Acrisols are found at elevations in the range of 0 to 2,500 m a.s.l., located mainly in the south and southeastern regions of Mexico in the states of Oaxaca, Chiapas, Veracruz and Tabasco. Andosols are found at elevations from 2000 to 4500 m a.s.l., located mainly along the Transvolcanic Belt, in the states of Jalisco, Michoacán, the State of Mexico, Mexico City, Morelos, Tlaxcala, Puebla, Hidalgo, Veracruz, Guerrero, and Chiapas. Upon fulfilling all inclusion requirements, at the national scale, we discovered a potential restoration area for C sequestration of 938.57 km$^2$ (2.60%) of Acrisols and 1,871.55 km$^2$ (8.03%) of Andosols (Fig. 2), which correspond to areas dominated by gullies. These areas would represent, in terms of soil condition, controlling erosion in 6.37% of the Acrisol affected area and 19.07% of the Andosol area. At the state scale, Acrisol areas are located in the states of Chiapas (527.87 km$^2$), and Oaxaca (358.09 km$^2$), at an elevation range of 1500-2000m asl. Andosol lands are located in the state of Michoacán (926.60 km$^2$), Puebla (331.19 km$^2$), Chiapas (315.43 km$^2$), Veracruz (198.11 km$^2$) and Estado de México (80.04 km$^2$) at elevations between 2000 and 3000 m a.s.l.

The two restored sites' aerial biomass had a C content of 1.41 t/ha for the older site and 1.15 t/ha for the more recent site, with an average of 1.27 t/ha. The sites were evaluated 15 and 11 years after they were established. In terms of soil carbon content, the top 10 cm had higher C accumulation, while deeper soil had lower C accumulation (Fig. 3). Carbon content for the entire profile was 4.25 t/ha. Gullies had no vegetation cover prior to the restoration trials and C content under these conditions was below the detection limit of the total C analyzer equipment (0.1%). However, the soil organic C content was very low in comparison with the soil C content of mature pine forest fragment in Acrisols (0-10 cm depth) or Andosols (0-20 cm depth): 115 ± 0.7 t/ha and 98 ± 13.7 t/ha, respectively (Galicia et al., 2016). These results suggest that the reforested gullies could capture significant amounts of C.

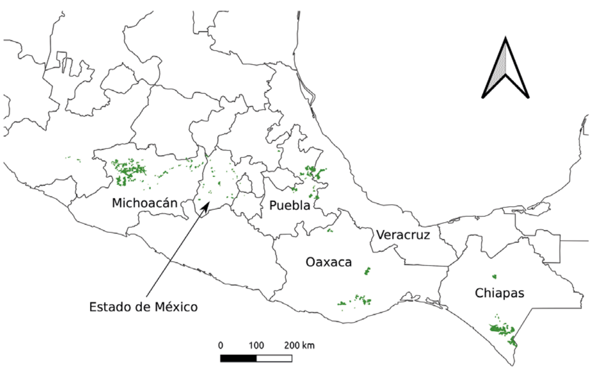


**Figure 2**. Location of severely degraded Acrisol and Andosol land areas with restoration potential for carbon sequestration purposes in Mexico.

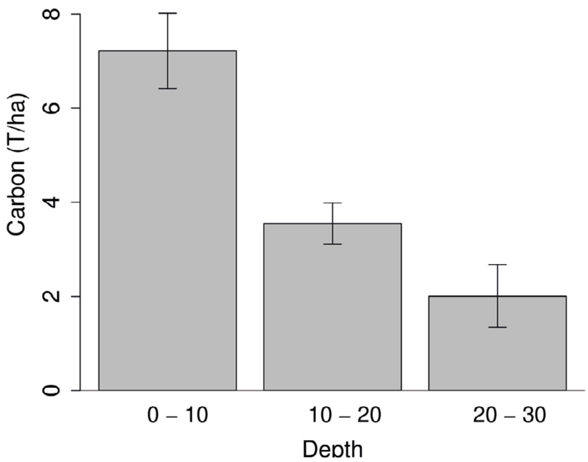


**Figure 3**. The relationship between soil depth and soil organic carbon content in the 13-year-old restored gully.

We estimated that potential C sequestration for an average period of 13 years for an area of 2810 km² was 3.947 megatons of C (MtC). A large percentage (89%) of potential capture is concentrated in four states in Mexico, Michoacán in the first place with 1.35 MtC in an area of 965.80 km$^2$, followed by Chiapas, with 1.18 MtC in 843.31 km$^2$ (Fig. 4). In calculating potential sequestration for each land type, we found that for Acrisols, the state with the greatest potential was Chiapas with 0.74 MtC in 527.87 km$^2$, followed by Oaxaca, with 0.50 MtC in 358.09 km$^2$. For Andosols, the state of Michoacán had the greatest potential with 1.30 MtC in 926.60 km$^2$, followed by Puebla, with 0.46 MtC in 331.19 km$^2$, and Chiapas, 0.44 MtC in 315.47 km$^2$.

Climate change will bring to Mexico an increase in temperatures and a decrease in rainfall (Sáenz-Romero et al., 2010). This might suggest that conditions for high erosion rates might decrease. But not only the amount of rainfall should be considered, but also the intensity of rainfall events. Worldwide data (Seneviratne et al., 2021) shows that extreme weather conditions are more common as a consequence of climate change, including heavy precipitation. For Mexico, our own field data from conifer forest restoration sites shows that in recent years the rainy season has shortened and that annual precipitation has decreased, but a higher volume of water can fall in a shorter period of time (Gómez-Pineda et al., 2021). Consequently, erosion processes might worsen, in particular if heavy precipitation is coupled with losses of vegetation cover caused by plant mortality during the dry season.

Restoration of severely degraded sites is usually very limited, except in cases when it is undertaken as part of mitigation projects mandated by law, due to the cost involved, and because recovery of ecosystem structures and functions is at best limited. Nevertheless, inaction in addressing this problem contributes to the increase in the degradation of whole watersheds. Our results show that severely degraded sites where gullying is dominant have

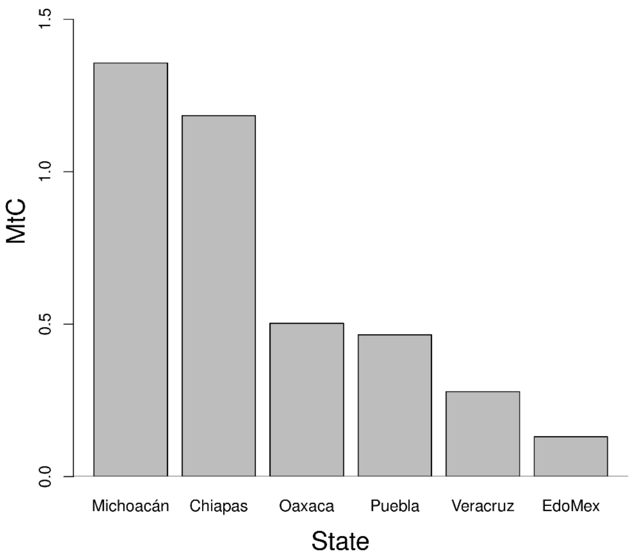


**Figure 4**. Potential carbon sequestration by Mexico's states: the four states shown account for 89% of the total.

a high potential for C sequestration of up to 0.3 MtC per year in the most severely degraded Acrisol and Andosol lands, representing 0.14% of the Mexican territory. Potential C sequestration would rise to 2.7 MtC annually if we take into account the approximately 24,000 km² of degraded Andosol and Acrisol areas that are located in Mexican territory (representing 1.25% of the country). Furthermore, severely degraded sites are an attractive option for restoration for C sequestration because: (i) social barriers associated with the restoration of these sites are few because there are no competing land uses; (ii) controlling gully formation prevents greater soil loss, and (iii) by applying strategies of assisted migration, these sites may serve as refuges for species whose habitats are disappearing due to the negative effects of climate change.

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