DOI: https://doi.org/10.29298/rmcf.v12i63.813

Article

Potencial de restauración de bosques de coníferas en zonas de movimiento de germoplasma en México

Potential of restoration of coniferous forests from germplasm transfer zones in Mexico

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Resumen

La restauración de tierras forestales requiere datos relacionados con el número de plántulas producidas y el nivel de degradación del suelo. Los tomadores de decisiones necesitan saber cuáles son los esfuerzos del programa nacional de reforestación como impulsor de la restauración de ecosistemas en México. Para evaluar el potencial de restauración de los bosques de coníferas y reducir la degradación de tierra en Zonas de Movimiento de Germoplasma (ZMG), se compararon zonas prioritarias para la restauración con los esfuerzos de reforestación más efectivos: porcentaje de sobrevivencia de plántulas plantadas, número de viveros (N), unidades de producción de germoplasma (UPG) y bancos de germoplasma (BG); para ello, se usó la base de datos de la Conafor correspondiente al periodo de 2016 a 2018. Se determinó que 27 ZMG tenían tierras forestales como áreas prioritarias: 7 418 975.30 ha de baja producción y 9 389 577.70 ha de degradación media y baja. De acuerdo con las variables utilizadas en el análisis comparativo, se identificaron ocho ZMG (XII.4, XII.5, X.3, X.2, XII.1, V.3, XII.2 y XV.1) como zonas de mayor potencial para la restauración, debido a que sus áreas prioritarias podrían ser reforestadas totalmente con especies de *Pinus* y *Abies*.

Palabras clave: *Abies*, *Callitropsis*, Conafor, degradación del suelo, *Pinus, Taxodium*.

Abstract

Forest land restoration requires data related to the number of seedlings produced and the level of soil degradation. Decision makers need to know the efforts of the national reforestation program as a driver of ecosystem restoration in Mexico. To assess the restoration potential of conifer forests and reduce land degradation by Germplasm Movement Zones (GMZ), priority zones for restoration were compared with areas that possess most effective restoration efforts: survival rate of planted seedlings, number of nurseries (N), Germplasm Production Units (GPU) and Germplasm Banks (GB) with data from Conafor corresponding to the 2016-2018 period. It was found that 27 GMZ had 7 418 975.30 ha of low-production forest land as priority areas and 9 389 577.70 ha of forest land with medium and low degradation. According to the variables used in the comparative analysis, eight GMZ (XII.4, XII.5, X.3, X.2, XII.1, V.3, XII.2, and XV.1) were identified as restoration potential zones because their priority areas could be totally reforested by using *Pinus* and *Abies* species.

Key words: *Abies*, *Callitropsis*, Conafor, soil degradation, *Pinus*, *Taxodium*.

Introduction

Terrestrial ecosystems provide a host of ecosystem services to humankind, including food, fodder, fiber, fuel and timber forest products. The demand for land products and services is degrading the ecosystems. About one third of the world's arable land is affected by degradation, which results in an increase in the number of people living in poverty in developing countries (Boer *et al.*, 2017).

Soil degradation is a serious global problem for many communities and is related to food insecurity, vulnerability to climate change and poverty (Barbier and Hochard, 2016). This degradation comes in various forms, including soil nutrient depletion, salinization, agrochemical contamination, soil erosion, vegetative degradation (e.g., deforestation) as a result of overgrazing, and the clearing of forests for use as farmland (Scherr and Yadav, 2001).

Deforestation is a major problem for developing countries because it causes loss of biodiversity and increases the greenhouse effect (Hein *et al.,* 2018). Most deforested areas occur in the temperate and subtropical zones (Angelsen *et al.*, 1999).

Around the world, there are several causes identified as the main drivers of deforestation: expansion of agricultural land, logging and firewood extraction, overgrazing, fires, mining, urbanization, military conflicts and tourism (Chakravarty *et al.*, 2012). All of these must be addressed by each country in order to reduce their impacts. Deforestation brings with it some problems that globally affect natural resources and the human population (Chakravarty *et al.*, 2012): climate change, loss of soil and water resources, flooding, decline in biodiversity, economic habitat loss, as well as social consequences. There are some essential strategies for reducing deforestation, which vary by region and time (Hein *et al.,* 2018).

In Mexico, temperate forests extend over an area of about 323 305 km^2 (around 17 % of the country), provide timber and non-timber resources, and are home to species essential to its biodiversity (Galicia *et al.*, 2015). However, these ecosystems have been reduced in almost 45 % of the country, due to increased land degradation (Semarnat-Colegio de Postgraduados, 2002). National projections for deforestation rates have varied from 260 000 to 1 600 000 ha year^{-1} over the past three decades, according to the record of academic studies and official reports (Couturier *et al.*, 2012).

The main causes of deforestation in Mexico are land use change for agriculture (82 %), illegal logging (8 %), as well as forest fires and diseases (6 %) (Goldstein *et al.*, 2011). The government's response has been to legislate and establish public policy programs (Goldstein *et al*., 2011; Cotler *et al.*, 2013), such as those of the Federal Environmental Protection Agency (Profepa), forest certification programs, afforestation and reforestation efforts, the creation of natural protected areas, and payment for environmental services programs. However, some other programs have favored or encouraged deforestation, including *Procampo* and *Alianza para el Campo*, since they promote agricultural activities at the cost of reducing forest areas (Schmook and Vance, 2009).

Mexico's National Forestry Commission (Conafor) established Germplasm Movement Zones (GMZs), equivalent to seed zones, defined as areas with similar ecological and climatic characteristics that host populations with relatively uniform genotypes or phenotypes (Flores *et al.*, 2014), in order to reduce the movement of germplasm out of its natural distribution. Zoning helps to increase the survival rate of established seedlings in the field, which is affected when species are planted outside their local distribution; therefore, they exhibit high mortality rates and poor adaptation to different growing conditions (Rehfeldt *et al.*, 2014). Although these zones have been defined, there is still a movement of germplasm among the GMZs that affects plant growth and diversity.

The reforestation program in Mexico is a permanent strategy to recover and increase forest areas and reduce forest land degradation; for example, in 2020 100 000 ha were reforested (FAO, 2020). However, the main problem is the low survival rate of seedlings (Burney *et al.*, 2015) which is associated with poor quality seedlings (Escobar-Alonso and Rodríguez, 2019). The low survival percentages cause that the goals of reforestation are not fulfilled, which seek to restore and to conserve the forests of the country.

In spite of the efforts to restore forests, none of the current degraded areas have been considered, nor have the level of degradation or the number of seedlings produced in nurseries per ecological zone or GMZ. The first is an area with wide formations of natural vegetation, but relatively homogeneous, similar in physiognomy although not necessarily identical (FAO, 2001). In order to propose a national restoration strategy, it is necessary to evaluate and use this information. Therefore, the objective of this research study was to assess the restoration potential of conifer forests in order to reduce land degradation by GMZs, by comparing priority areas for restoration with the most effective reforestation efforts.

In this regard, the following questions were raised: 1) Does the amount of seedlings vary among conifer species produced in the nurseries?; 2) Is the deterioration of land that is home to conifers dissimilar in different production zones and restoration zones by ZMG?; 3) Does the survival rate of seedlings vary for conifers by GMZ?; and 4) Is the restoration potential of conifers different within each GMZ?

This information is essential for planning reforestation actions to be initiated in order to restore those areas with soil degradation problems through the use of conifers.

Materials and Methods

The restoration potential to reduce soil degradation in the Germplasm Movement Zones (GMZ) of Mexico was analyzed (Conafor, 2016), based on comparisons between priority areas (production areas and restoration areas) and effective reforestation efforts (percentage survival of planted seedlings, number of nurseries, germplasm production units and germplasm banks).

Production areas are forest lands that, according to the structure and composition of vegetation, are subject to forest exploitation (Semarnat, 2015); while the restoration zones are forest areas with degradation evidence, with different degrees of progress and that constitute a risk from the loss of the forest resource that they may represent (Semarnat, 2015). The germplasm production units are areas established in natural stands, plantations or nurseries, with individuals belonging to a forest species, selected by their genotype or phenotype, whose origin is well identified, and which are used for the production of fruits, seeds or vegetative material (Conafor, 2016).

From Conafor data (2019a), the most commonly produced conifer genera and species were defined, and their average values of total seedlings planted from 2016 to 2018. This database has information on reforestation and conservation programs at the national level, which is used annually to write government reports. The conifer taxa were chosen because they cover most of the GMZs and produce different services for the population; for example, environmental services, timber production (Díaz-Núñez *et al.*, 2016), and organic carbon storage (INECC, 2015).

Based upon the information of the National Forest and Soil Inventory, corresponding to the 2004 - 2007 period (Conafor, 2017), the surface land of the production and restoration areas was estimated using the production and restoration maps of Conafor (2020). This institution classified six types of forest land productivity: High production forest land (II.A); Medium production forest land (II.B); Low production forest land (II.C); Land in arid zones (II.D); Land for reforestation (II.E); and Land for forestry activities (II.F). In addition, five types of soil degradation: Forest lands with high soil degradation (III.A); Severely eroded forest land (III.B); Forest lands with average degradation (III.C); Forest lands with low degradation (III.D); and Degraded forest land with management for restoration (III.E). Of these, II.C, and III.C and III.D were chosen as priority areas, because they could be restored in a short time (Flores *et al.*, 2019b).

The effective reforestation efforts in each GMZ were assessed using the percentage of seedling survival defined by Conafor (2010), as well as the number of established nurseries (N), defined Germplasm Production Units (GPU) and installed germplasm banks (GB), according to Conafor's records. This information was used because it directly supports the production of coniferous seedlings in the country. In each GMZ, the area that can be reforested with 1 100 plants ha^{-1}, and the average survival rate were estimated based on their registered percentages (Conafor, 2010). GMZs with a high planted seedling survival rate and the highest amount of N, GPUs and GBs were considered the areas with the most effective reforestation efforts.

Finally, the priority areas for restoration were compared with those with the most effective reforestation efforts in order to define the restoration potential sites.

Results

Conifer species and priority areas

Pinus, *Abies*, *Callitropsis*, *Cupressus* and *Taxodium* were identified as the main genera produced in nurseries from 2016 to 2018, particularly *Pinus* with 21 species; *Abies*, with one; *Callitropsis*, with one; *Cupressus*, with one, and *Taxodium*, with one. The *Pinus* genus was the most important, because it had 99.37 % (112 722 060 seedlings) of the total production; followed by *Abies* with 0.61 % (697 533 seedlings); *Callitropsis*, 0.01 % (11 667 seedlings); *Taxodium*, 0.01 % (8 000 seedlings); and *Cupressus* less than 0.01 % (313 seedlings). For pines, seven species (*Pinus cembroides* Zucc., *P. pseudostrobus* Lindl., *P. oocarpa* Schiede ex Schltdl., *P. devoniana* Lindl., *P. engelmannii* Carrière, *P. montezumae* Lamb., and *P. greggii* Engelm.) accounted for 76.36 % of total production (Table 1), and were the most used in the reforestation of various areas.

Table 1. Conifer seedlings produced in Mexico in the 2016 – 2018 period.

Species	Seedling production per year			
	2016	2017	2018	Mean
Pinus cembroides Zucc.	21 255 465	22 517 497	18 855 651	20 876 203
P. pseudostrobus Lindl.	16 591 232	20 101 970	14 321 405	17 004 869
P. oocarpa Schiede ex Schltdl.	12 685 000	14 827 111	12 796 008	13 436 040
P. devoniana Lindl.	12 267 395	13 270 311	9 004 483	11 514 063
P. engelmannii Carrière	9 354 850	10 037 175	9 269 549	9 553 858
P. montezumae Lamb.	10 325 600	10 455 847	6 982 449	9 254 632
P. greggii Engelm.	8 677 500	8 863 885	7 600 432	8 380 605
P. hartwegii Lindl.	3 954 287	4 543 802	3 071 176	3 856 422
P. patula Schiede ex Schltdl. *et* Cham.	4 645 153	4 005 461	2 709 233	3 786 616
P. arizonica (Engelm.) Shaw	3 513 900	3 531 166	3 122 813	3 389 293
P. douglasiana Martínez	3 441 500	2 966 698	1 515 512	2 641 236

P. teocote Schiede ex Schltdl. *et* Cham.	2 529 590	2 148 060	1 741 061	2 139 571
P. ayacahuite Ehrenb. ex Schltdl.	2 124 447	2 253 893	1 961 985	2 113 442
P. leiophylla Schiede ex Schltdl. *et* Cham.	2 534 000	1 659 745	1 714 405	1 969 384
P. durangensis Martínez	1 543 750	1 789 974	1 286 617	1 540 114
Abies religiosa (Kunth) Schltdl. *et* Cham.	797 315	957 200	338 085	697 533
P. lawsonii Roezl ex Gordon	600 000	500 000	514 000	538 000
P. chiapensis (Martínez) Andresen	950 000	340 000	252 140	514 046
P. maximinoi H. E. Moore	300 000	0	150 000	150 000
P. jeffreyi Balf.	55 000	75 000	40 000	56 667
Callitropsis arizonica (Greene) D. P. Little	0	2 000	33 000	11 667
Taxodium mucronatum Ten.	10 000	10 000	4 000	8 000
P. maximartinezii Rzed.	0	0	15 000	5 000
P. quadrifolia Parl. ex Sudw.	6 000	0	0	2 000
Cupressus sempervirens L.	500	0	440	313
Total	118 172 484	124 856 795	97 299 444	113 442 908

Source: Conafor (2019a).

It was determined that 27 GMZs harbored the species produced in nurseries, and also had fewer priority areas II.C than III.C and III.D; specifically, four GMZs exhibited 16 to 20 taxa; eight exhibited 11 to 15; five, six to 10, and ten, one to five (Table 2). Six zones (III.1, III.2, III.4, III.3, XII.3, V.1) registered 75.26 % of the forest land areas with the lowest production (5 583 604.98 ha); while 21 zones had only 24.74 % (1 835 370.32 ha). Also, five GMZs (III.1, III.2, IV.1, III.3, V.1) were obtained with 74.60 % medium- and low-degradation Forest Lands with (7 004 954.96 ha); however, 22 areas had only 25.40 % (2 384 622.74 ha). Also, two zones represented 42.54 % of the total area with II.C, III.C and III.D.

Table 2. Priority species and areas in Mexico by ZMG.

GMZ	Species¶	Priority areas (ha)‡	
		(II.C)	**(III.C and III.D)**
I.1	Pce, Pje, Pqu	116 107.41	86 110.66
I.2	Pce	196 881.36	43 588.40
III.1	Pce, Are, Car, Pay, Par, Pdo, Pdu, Pen, Ple, Poo, Pps, Pte	1 768 847.03	2 327 879.91
III.2	Pce, Are, Car, Pay, Par, Pch, Pde, Pdo, Pdu, Pen, Ple, Pma, Poo, Pps, Pte	1 388 616.84	1 665 144.76
III.3	Pce, Pay, Par, Pch, Pde, Pdo, Pdu, Pen, Ple, Pma, Poo, Pps, Pqu, Pte	765 137.93	1 022 176.48
III.4	Pce, Pay, Par, Pde, Pdo, Pdu, Pen, Ple, Pma, Pmm, Poo, Pps, Pte	837 030.14	301 375.50
IV.1	Pce, Pde	77 513.00	1 252 324.67
V.1	Pce, Car, Par, Pen, Ple, Pqu, Pte	222 136.23	737 429.14
V.2	Pce, Car, Par	113 026.44	390 801.00
V.3	Pce, Car, Pay, Par, Pch, Pde, Pen, Pgr, Pha, Pmo, Poo, Ppa, Pps, Pqu, Pte, Tmu	205 329.70	463 612.09
VIII.1	Pps, Tmu	133 563.38	288 376.53
VIII.3	Pps	9 713.93	111 754.80
VIII.4	Pte	977.06	8 735.48
IX.2	Pce, Pay, Pde, Pdu, Pte	95 816.63	71 800.57
X.1	Pce, Are, Pde, Pdo, Pdu, Pen, Pha, Ple, Pma, Poo, Pps, Pte	145 822.67	203 923.04
X.2	Are, Pde, Pha, Pla, Ple, Pmo, Poo, Ppa, Pps, Pte	133 071.64	13 881.94
X.3	Pce, Are, Pay, Pch, Pde, Pdo, Pdu, Pgr, Pha, Pla, Ple, Pma, Pmo, Poo, Ppa, Pps, Pte, Tmu	163 041.67	114 867.96
XII.1	Are, Pay, Pde, Pdo, Pen, Pha, Pla, Ple, Pma, Pmo, Poo, Ppa, Pps	18 300.56	4 778.01
XII.2	Pay, Pch, Pde, Pdo, Pha, Pla, Pma, Pmm, Poo, Pps, Pte	52 711.91	13 317.33

XII.3	Pce, Are, Cse, Pay, Pch, Pde, Pdo, Pdu, Pgr, Pha, Pla, Ple, Pma, Pmm, Pmo, Poo, Ppa, Pps, Pte, Tmu	601 836.81	134 822.56
XII.4	Are, Pay, Pde, Pdo, Pen, Pha, Pla, Ple, Pma, Pmm, Pmo, Poo, Ppa, Pps, Pte	92 642.28	26 388.95
XII.5	Pce, Are, Pay, Pch, Pde, Pdo, Pha, Pla, Ple, Pma, Pmm, Pmo, Poo, Ppa, Pps, Pte	127 157.04	20 193.11
XIII.1	Poo, Pps	39 905.21	21 037.32
XIV.1	Pce, Pay, Pde, Pma, Pmo, Poo, Pps, Pte	86 038.32	41 522.77
XIV.2	Pde, Pma, Pmm, Pmo, Poo, Pps, Pte	8 724.39	10 468.94
XIV.3	Poo	2 100.00	138.17
XV.1	Pde, Pdo, Pma, Pmm, Poo, Pps, Pte, Tmu	16 925.72	13 127.61
Total		7 418 975.30	9 389 577.70

Source: Conafor (2020).

¶:Are = *Abies religiosa,* Car = *Callitropsis arizonica,* Cse = *Cupressus sempervirens,* Pay = *Pinus ayacahuite,* Par = *P. arizonica,* Pce = *P. cembroides,* Pch = *P. chiapensis,* Pde = *P. devoniana,* Pdo = *P. douglasiana,* Pdu = *P. durangensis,* Pen = *P. engelmannii,* Pgr = *P. greggii,* Pha = *P. hartwegii,* Pje = *P. jeffreyi,* Pla= *P. lawsonii,* Ple = *P. leiophylla,* Pma = *P. maximinoi,* Pmm = *P. maximartinezii,* Pmo = *P. montezumae,* Poo = *P. oocarpa,* Ppa = *P. patula,* Pps = *P. pseudostrobus,* Pqu = *P. quadrifolia,* Pte = *P. teocote,* Tmu = *Taxodium mucronatum*. ‡II.C = Low production forest lands, III.C and III.D = Forest lands with medium and low degradation.

Effective reforestation efforts

For the seedling survival percentages per GMZ, 10 zones were identified with values of 60.38 to 74.95 %; eight, with 46.99 to 58.55 %; five zones with 34.81 to 37.55 %, and four zones with values of 11.85 to 14.72 % (Figure 1).

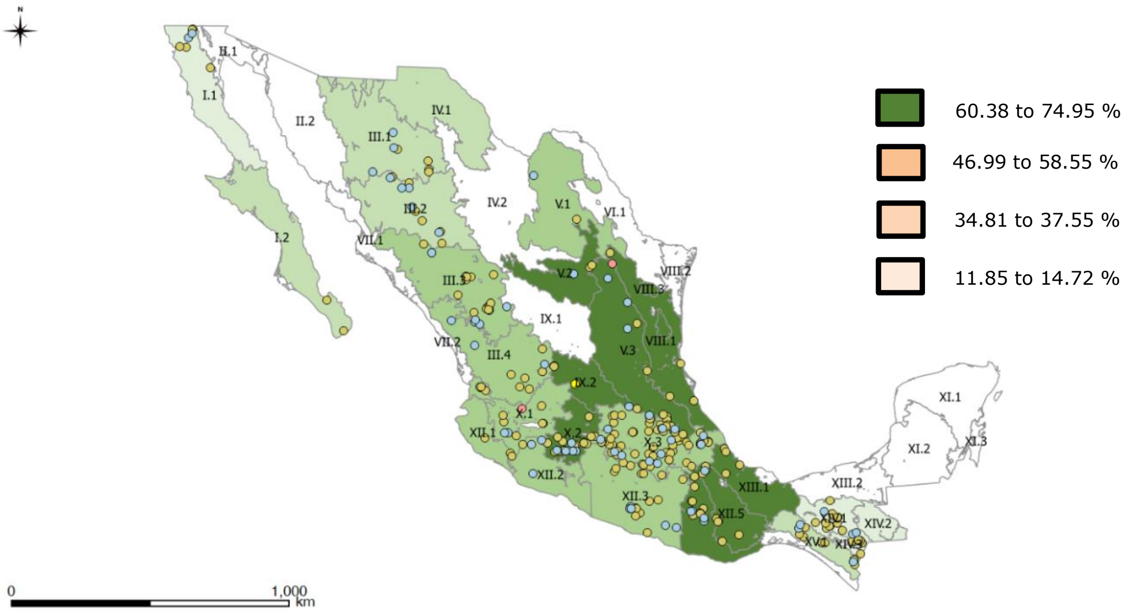

Figure 1. Survival rates (green colors) and nurseries (yellow circles), germplasm production units (blue circles), and germplasm banks (pink circles) in the GMZs.

Pinus oocarpa varied in all survival rates, while *P. pseudostrobus* and *P. teocote* were the most frequent pines, with higher, medium, and lower survival rates; *P. devoniana* occurred more frequently in high and medium percentages; in contrast, *P. ayacahuite*, *P. cembroides*, *P. devoniana*, *P. douglasiana*, *P. durangensis*, *P. engelmannii*, *P. hartwegii*, *P. leiophylla*, *P. maximinoi* had medium percentages, and *P. cembroides*, *P. douglasiana* registered low values.

As for the number of nurseries, one zone had the most (72), five had a considerable number (13 to 19), 17 zones had few (1 to 8), and four zones had none (Table 3). One zone accounted for the largest number of GPUs among the established units (14), while 17 zones had one to six, and nine zones had none. On the other hand, seven zones had very few GBs (1 to 5), and 20 zones lacked germplasm banks altogether (Figure 1, Table 3).

Table 3. Number of nurseries, germplasm production units and germplasm banks by GMZ.

GMZ	Nurseries	GPUs	GBs
I.1	5	2	-
I.2	2	-	-
III.1	5	3	-
III.2	5	6	-
III.3	15	6	1
III.4	7	3	-
IV.1	-	-	-
V.1	1	1	-
V.2	2	1	-
V.3	8	5	1
VIII.1	4	-	-
VIII.3	-	-	-
VIII.4	-	-	-
IX.2	2	1	-
X.1	17	3	2
X.2	16	5	1
X.3	72	14	5
XII.1	1	-	-
XII.2	1	2	-
XII.3	13	5	-
XII.4	7	4	-
XII.5	7	1	1
XIII.1	4	-	-
XIV.1	19	3	-
XIV.2	-	-	-
XIV.3	2	-	-
XV.1	8	3	-

GPU = Germplasm Production Unit; GB= Germplasm Bank.

Areas with restoration potential

Eight GMZs (XII.4, XII.5, X.3, X.2, XII.1, V.3, XII.2 and XV.1) were detected as areas with restoration potential because they could be fully reforested; zone X.3 had the largest number of nurseries, GPUs and GBs. In addition, one zone exhibited low/production areas (X.1), and another, areas of medium and low degradation (XII.3) that are susceptible to be completely restored. Four zones were considered to have the capacity to restore between 18.14 and 29.15 % of their areas (XIV.2, XIV.1, III.3 and III.4), and they include a significant number of nurseries and GPUs. It is viable to restore 3.44 to 8.58 % of the area of zones III.2, III.1 and IX.2, which had the lowest survival percentages, as well as few nurseries and GBs. In the last 10 zones, it is only possible to restore less than 3 % of the area, since, unfortunately, they have few nurseries and GPUs and no GBs.

Discussion

This research evaluated the potential of certain Mexican conifers to reduce forest land degradation in the GMZs, through the reforestation program, in order to provide a basis for the implementation of a restoration strategy for temperate forests. The results of this study showed that the number of seedlings produced in nurseries, land degradation and survival rate were different for the selected conifers, and their restoration potential varies among the GMZs. Consequently, during the reforestation process in the GMZs, the species studied were able to restore many forest lands with medium (III.C) and low degradation (III.D).

Pinus, *Abies*, *Callitropsis, Cupressus* and *Taxodium* were the main genera used in nurseries and reforestation programs. *Pinus* was the most produced during the 2016 - 2018 period; while the lowest figures corresponded to *Taxodium*; there was little production of *Abies*, *Cupressus* and *Callitropsis*. The number of seedlings in nurseries depends on the seeds available and collected in state stands (Conafor, 2019b).

Pinus species are the most widely distributed in the country, compared to other conifers (Farjon and Filer, 2013); therefore, they have been the most commonly used by nurseries. For example, *P. cembroides*, *P. oocarpa* and *P. pseudostrobus* are distributed along different temperate mountain ranges as pure conifer and mixed forests (Rzedowski, 1979; Flores *et al.*, 2011; Farjon and Filer, 2013; Flores *et al.*, 2019a) and are the most widely used for the production of seedlings. On the other hand, some pines are very important for obtaining wood (Sánchez-González, 2008), for the sawmill industry and for resin production (Fuentes *et al.*, 2006), as well as for the establishment of commercial plantations (López-Upton *et al.*, 2005); therefore, they are quite frequently grown in nurseries each year.

Land degradation (II.C, and III.C and III.D) varied among the GMZs and presented different species of conifers; that is, the productivity of forest lands in II.C registered a smaller area of degradation, with 24 species (except *P. jeffreyi*), than land degradation types III.C and III.D with 16 species (*Cupressus sempervirens*, *P. greggii*, *P. hartwegii*, *P. jeffreyi*, *P. lawsonii*, *P. maximartinezii*, *P. montezumae*, *P. patula*, *T. mucronatum* were absent). This proved that the areas of II.C can be restored in a short time, but they need a great investment; for example, between the 2002 - 2007 period, almost 157 653 ha year^{-1} (27.85 % of the national forest area) were deforested in *Chihuahua, Durango, Coahuila, Guerrero, Nuevo León, San Luis Potosí, Zacatecas* and *Tamaulipas* (Masek *et al.*, 2011), and large investments have been required for their restoration.

The efforts made to implement the reforestation program have been significant in the restoration areas, but are still insufficient for some states, despite the fact that reforestation and soil improvement activities have been developed since 1999 (Ceccon *et al.*, 2015).

The reforestation rate in the country is not enough; it is estimated that, in order to recover 43.5 million ha of degraded soils 400 000 ha must be reforested per year and approximately 68 million U.S. dollars must be invested; however, the Mexican government reforests only around 193 000 ha per year (Ceccon *et al.*, 2015) and invests merely 32 million U.S. dollars (Sánchez-Velásquez, 2009).

The survival rates of the evaluated conifers varied among the GMZs. Most species had different survival values; *P. pseudostrobus* and *P. teocote* were the most frequent, with higher, medium and lower survival rates. This shows that species with high percentages of field survival —*e.g., P. cembroides* with 81 % (Gómez-Romero *et al.*, 2012); *P. pseudostrobus* with 86 to 62 % (Gómez-Romero *et al.*, 2013); *P. devoniana* with 71 % (Blanco-García *et al.*, 2008)— exhibit a high production of seedlings in nurseries and could be used for restoration works. Species with medium or low production also have an important survival rate, as indicated by Gómez-Romero *et al.* (2012) for *P. hartwegii* (89 to 82 %) and *P. devoniana* (80 %).

The species selected for nursery production should be tolerant to water deficit or even drought —as it happens with *P. cembroides*, which is resistant to adverse conditions of rainfall, soil, frost, drought and high temperatures (Flores *et al.*, 2018; Gutiérrez-García *et al.*, 2015)— as, due to climate change, they are likely to experience drier conditions and water stress during their growth in the field. In addition, the selected taxa must have the ability to grow in substrates that limit their establishment, as is the case of *P. leiophylla*, a taxon whose seedlings reach significant height when produced on mine booty substrate, while *P. devoniana* has appreciable growth (Osuna-Vallejo *et al.*, 2017). For eroded areas, soil formation through the use of conifer taxa is another aspect to consider in species selection.

The restoration potential of conifers was different within the GMZ. The results clearly suggest that in a relevant number of zones (eight) their priority areas could be reforested, since both the production of seedlings and their different survival percentages indicate it. In this regard, the number of planted seedlings (1 100 plants ha^{-1}) with their percentages of survival in the field are sufficient to cover these areas, although they only represent 8.80 % of the total of areas II.C, III.C and III. D.

Pinus devoniana, *P. oocarpa*, *P. pseudostrobus*, *P. halepensis*, *P. teocote*, *P. ayacahuite*, *P. douglasiana*, *P. lawsonii*, *P. maximinoi*, *P. montezumae*, *P. patula* and *A. religiosa* were the taxa with the greatest presence in the GMZs.

In order to propose a program to restoration degraded areas, it is necessary to define different densities and species which support the restoration process, for example *P. pseudostrobus, P. engelmannii, P. montezumae, P. greggii, P. arizonica and P. durangensis* could be used to restore III.C and III.D areas (Flores *et al*., 2019).

Seedling survival is an important factor to consider when reforesting. It is estimated that, in Mexico, reforested areas reach a low (36 %) (Wallace *et al.*, 2015) or medium (50 %) (Burney *et al.*, 2015) average of seedling survival after their first year, due to poor seedling quality and drought. Therefore, it is suggested that local seedlings be used in reforestation projects to increase the potential for acclimatization (Sáenz-Romero and Guries, 2002) and reduce the risk of death from drought.

The X.3 zone was the most important for the restoration potential, because it includes many nurseries, GPUs and GBs; this shows that X.3 has a good effort within the reforestation program (Flores *et al.*, 2019b).

For forest owners, conifers are interesting trees to use in reforestation areas; thus, in the region surrounding the Monarch Butterfly Biosphere Reserve, their restoration potential has been an important factor in the decision to use them to reforest agricultural plots and degraded forests (Honey-Rosés *et al.*, 2018). In order to promote soil conservation practices with conifer taxa, the government has implemented the Forest Soil Conservation and Restoration Program, which pays a subsidy to landowners. This action aims to reduce the estimated land degradation in the country by 45 % (Semarnat-Colegio de Postgraduados, 2002).

In the restoration areas, it is necessary to increase the efforts of the reforestation program (nurseries, GPUs and GBs); furthermore, restoration failures —*i.e.,* the high initial mortality, deficient growth and susceptibility to biotic and abiotic stressors, due to the misuse of the source and the genetic quality of the forest reproduction material— must be avoided (Godefroid *et al*., 2011). Appropriate attention to the genetic quality of germplasm is important for a forest restoration that seeks to adapt tree species to changing conditions (White *et al.*, 2007).

Conclusions

In recent decades, the surface area of Mexico's temperate forests has been reduced due to increased land degradation. The reforestation program is an ongoing strategy to increase forest areas and reduce forest land degradation with *Pinus*, *Abies*, *Callitropsis, Cupressus* and *Taxodium*. *Pinus cembroides*, *P. pseudostrobus*, *P. oocarpa*, *P. devoniana*, *P. engelmannii*, *P. montezumae* and *P. greggii*, which add up to 76.36 % of the total production in nurseries during the analyzed period. In addition, these taxa are distributed in 27 GMZs, which have 7 418 975.30 ha of low-production forest land (II.C) and 9 389 577.70 ha of medium- and low-degradation forest land (III.C and III.D).

In the GMZs, 10 zones are identified with higher survival rates: eight with medium values, five with low values, and four with lower values. As for the number of nurseries, one area contains the majority of the nurseries; five areas include a considerable amount of them; 17 include few, and four areas include none.

One zone includes most of the established GPUs, while 17 zones have few units, and nine zones have none at all. In seven zones there are very few GBs, and none in 20. Eight GMZs have restoration potential, since they can be fully reforested, but zone X.3 alone includes more nurseries, GPUs and GBs, compared to the others.

Acknowledgements

The authors thank Conafor for providing the data and information cited in the document.

Conflict of interests

The authors declare that no conflict of interests.

Contribution by author

Andrés Flores: research approach, data analysis and drafting of the manuscript; Ramiro Perez-Miranda: geographic information analysis; Martin Enrique Romero-Sánchez and Francisco Moreno-Sánchez: review and editing of the manuscript; Tomás Pineda-Ojeda: supervision of the research study.

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