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Review article

Aportaciones científicas del Programa de Plantaciones Forestales en el INIFAP

Scientific contributions from the Forest Plantation Program at INIFAP

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Resumen

El Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP) cuenta con seis Sistemas Forestales (SF) para fortalecer la investigación. Dentro de ellos, el Sistema de Plantaciones Forestales (SPF) incluye tres líneas de investigación, nueve productos por obtener y tres objetivos específicos. El objetivo de este trabajo fue compilar y analizar la información de publicaciones de investigación en libros y revistas científicas realizadas en el SPF del INIFAP a los 35 años de su creación. Se hizo una búsqueda en sitios de la web de publicaciones entre 1985 y 2021 de libros y artículos científicos, usando palabras clave. Se analizaron nueve trabajos relacionados con la caracterización ecológica de hábitat degradado, que son la base para el establecimiento de plantaciones forestales de reforestación (PFR) con al menos 86 especies de importancia comercial, 26 sobre producción de plantas de calidad que han tenido impacto en componentes para producir millones de plantas y 61 para establecimiento y manejo de PFC, donde 84.2 % son sobre el crecimiento de las especies, de las cuales en 2020 se reporta la existencia de 230 341 ha de PFC y 101 577 ha de sistemas agroforestales (SA).

Estas investigaciones han sido la base para implementar programas de desarrollo que contribuyen a la economía de los habitantes rurales a nivel regional y nacional.

Palabras clave: Cambio climático, germoplasma, modelación forestal, plantaciones forestales, potencial productivo, producción de plantas.

Abstract

The National Institute for Research on Forests, Agriculture and Livestock (INIFAP) has six Forest Systems, among them, the Forest Plantations System (FPS), which includes three research lines, nine products to be obtained, and three specific objectives. The aim of this work was to compile and analyze information of research publications in books and scientific journals made in the FPS 35 years after the creation of INIFAP. A search was made on the websites of publications between 1985 and 2021 of books and articles in scientific journals, using keywords. We analyzed 9 works related to the ecological characterization of degraded habitat, 26 on the production of quality plants that have had an impact on components to produce millions of plants, and 61 for the establishment and management of CFPs; 84.2 % deal with the growth species, of which in 2020 the existence of 230 341 ha of CFPs and 101 577 ha of agroforestry systems (AS) were reported. These research studies have served as the basis for implementing development programs that contribute to the economy of rural inhabitants at the regional and national levels.

Key words: Climate change, germplasm, forest modeling, forest plantations, productive potential, plant production.

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Review article

Introduction

Worldwide commercial forest plantations (CFP) are a strategy for increasing production, reducing raw material deficits, generating development, and lowering the pressure on natural forests. Between 2000 and 2010, the area of CFPs increased by 6 %. By 2016, these covered 264 million hectares (7 % of the global forest area); 30 % were concentrated in Asia, most of them for industrial purposes (FAO, 2016).

In *San Luis Potosí*, Mexico, a 6 400 ha CFP of *Eucalyptus* spp. was established in the 1950s, and in *Oaxaca*, from 1974 to 1980, 10 000 ha were planted with *Pinus caribaea* var. *hondurensis* Bar. and Golf. (Prodefo, 2000).

Since 2000, the National Forest Commission (Conafor) launched the Commercial Plantation Development Program (Prodeplan), and by 2019, 230 341 ha (78.38 % of the national total) had been planted in eight states of the country; mainly, with *Eucalyptus grandis* W. Hill, *Eucalyptus urophylla* S. T. Blake (21 %), *Cedrela odorata* L. (17 %), *Gmelina arborea* Roxb. (11 %), *Pinus* sp. (10 %), *Swietenia macrophylla* King (9 %), *Tectona grandis* L. f. (9 %), *Agave lechuguilla* Torr. (7 %), *Hevea brasiliensis* (Willd. ex A. Juss.) Müll. & Arg. (4 %), *Chamaedora* spp. (3 %), *Tabebuia rosea* (Bertol.) DC. (2 %), certain species of Christmas pine (2 %), and other taxa (Conafor, 2020).

On the other hand, since the creation of the National Institute for Research on Forests, Agriculture and Livestock (INIFAP) in 1985, there has been a Forest Plantations Program (FPP), which today has three lines of research and gives rise to nine products (Table 1); this program has generated technologies for plant production, establishment, evaluation, and management of CFPs (INIFAP, 2018).

Table 1. Lines of research and products to be obtained in INIFAP's FPP.

Research line	Products
1. Ecological characterization of degraded habitat	1.1 Technology for the establishment and management of FPs for reforestation purposes (RFP)
2. Technology for the production of quality forestry plants	2.1. Methods for the conservation and propagation of recalcitrant priority and endemic species
	2.2. Technology for quality plant production
3. Establishment and management of CFPs	3.1. Technology for the establishment and management of CFPs
	3.2. Growth, increment, and yield models for CFPs
	3.3. Volume tables and production tables by species
	3.4. Production potential maps for CFPs
	3.5. Maps showing areas of productive potential for CFPs under the climate change scenario
	3.6. Indicators of biomass productivity and carbon sequestration in FPs

Source: INIFAP (2018).

Thus, the objective of this document is to compile and analyze the information on research publications in books, special publications and scientific journals by researchers of INIFAP's PPF, 35 years after its creation.

Methodology

A search of publications generated between 1985 and 2021 —including scientific books, technical books, special publications and scientific journals was made— was made on websites such as Docplayer, Google Chrome, Google Scholar, Redalyc, *ResearchGate*, and SciELO; the keywords used were the names of researchers, titles of papers, terms related to lines of research, products and objectives of INIFAP's FPP. Since some documents include more than one species, each species was referred to as a study. Frequencies of the information obtained and impacts to which the technologies have contributed at the regional or national level were obtained according to the lines of research and products that make up INIFAP's FPP (2018) (Table 1).

The search resulted in 97 publications, with an annual average of 2.7 publications, distributed among the three lines of research of INIFAP's FPP (Table 1; figures 1 and 2).

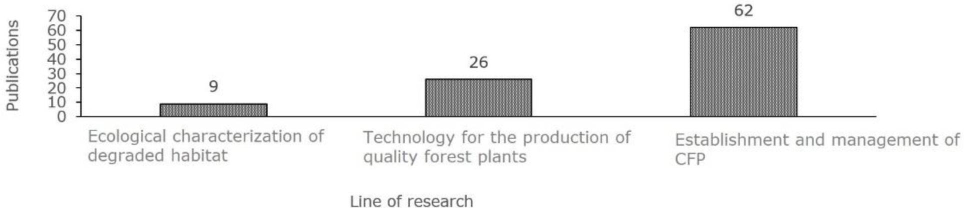

Figure 1. Publications by line of research of INIFAP's FPP.

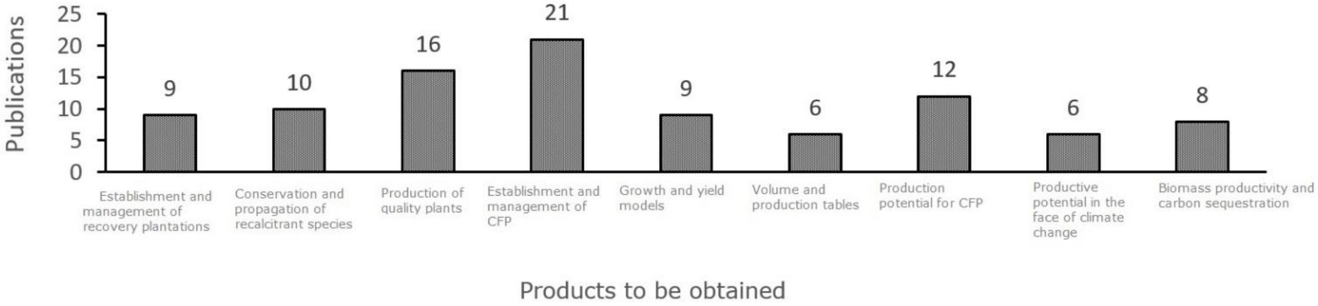

Figure 2. Publications by product of the INIFAP's FPP.

The number of publications increased from 2011 to 2021, years in which 71.9 % of the documents reviewed were published (Figure 3).

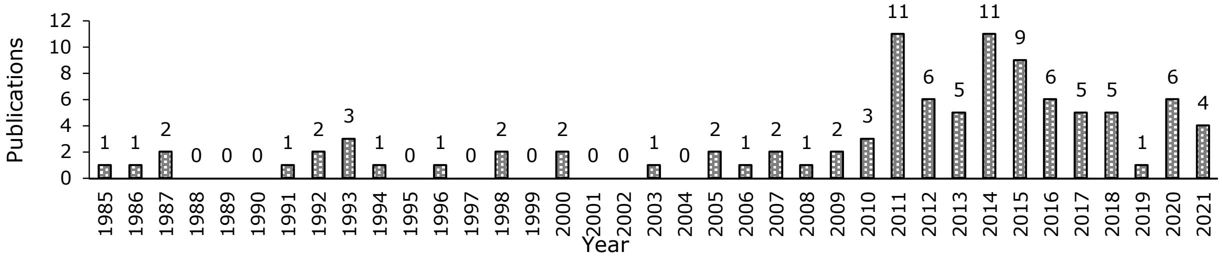

Figure 3. Annual publications of INIFAP's FPP.

In the 97 publications included in this review, 128 species were researched in 228 studies (Figure 4).

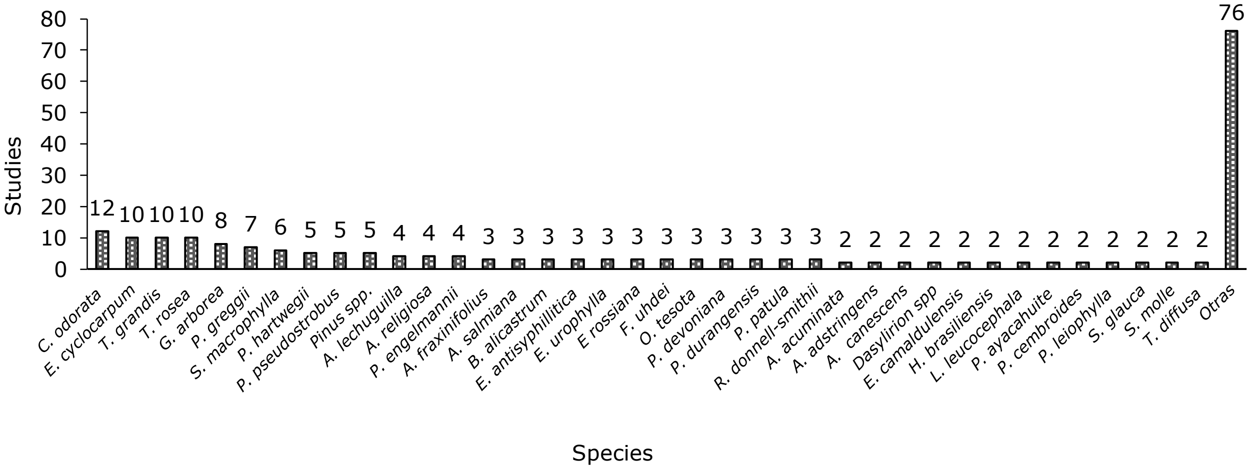

Figure 4. Studies by species published by researchers of INIFAP's FPP.

Ecological characterization of degraded habitat

Nine studies were found on 86 species of commercial importance; Figure 5 shows that the characterization of the species and their uses and management account for 87.9 % of the studies.

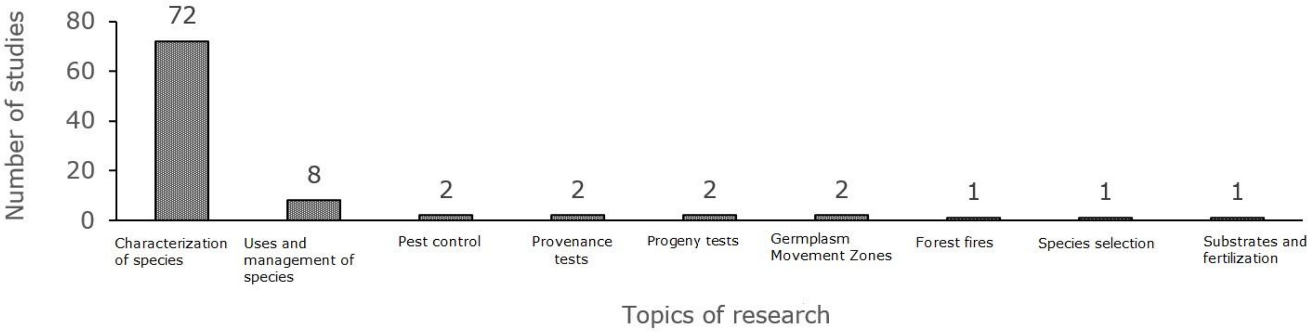

Figure 5. Topics of research line 1.1 in INIFAP's FPP.

In temperate forests of *Chihuahua*, Alarcón and Iglesias (1992) determined the best substrate mixtures and fertilization routines for producing *Pinus durangensis* Martínez seedlings in greenhouses; Muñoz *et al.* (2010) evaluated *Pinus patula* Schiede ex Schltdl. & Cham. in RFPs, protection plantations (PPs), and CFPs of *Michoacán* and conclude that the *Purépecha Sierra* has appropriate areas for its establishment. Rueda *et al*. (2013a) characterized 72 forest species, their requirements and potential zones for the establishment of forest plantations in *Jalisco.*

Hernández and Benavides (2015) tested the sensitivity to photochemical oxidants due to the effect of ozone on *Abies religiosa* (Kunth) Schltdl. *et* Cham. and *P. hartwegii* Lindl. in the State of Mexico and determined a foliage damage index for the 20 provenances studied; while Flores *et al*. (2021) identified Germplasm Movement Zones (GMZ) for restoration with *Pinus* and *Abies* species and determined that 27 ZMG corresponded to forest lands as priority areas: 7 418 975 ha of low production and 9 389 577 ha of medium and low degradation.

For the tropical ecosystem, Rodríguez *et al.* (1993) evaluated in the nursery the progenies of *Dendropanax arboreus* (L.) Decne. & Planch. and *Simarouba glauca*

DC. with the best development; Sánchez and Velázquez (1998) achieved the control of larvae of *Hypsipyla grandela* (Zeller) in *Cedrela odorata* L. with *Beauveria bassiana* (Bals.-Criv.) Vuill. in 71 % of the trees, and with *Bacillus thuringiensis*, in 91 %. In *Quintana Roo*, García *et al.* (2010) evaluated seed dispersal by aircrafts, germination, and growth of *Enterolobium cyclocarpum* (Jacq.) Griseb. in burned areas; after 90 days, 25 % of the dispersed seeds produced seedlings with an average height of 40 cm.

For arid zones, Martinez (2013) compiled information on *Lippia berlandieri* Schauer, *Prosopis* spp., *Agave lechuguilla*, *Dasylirion* spp., *A. salmiana* B. Otto ex Salm-Dyck ssp. *crassispina* (Trel.) Gentry, *Euphorbia antisyphilitica* Zucc., *Turnera diffusa* Willd. ex Schult. and *Olneya tesota* A. Gray. in natural populations and classified the productive potential and zoning for their use and conservation.

In Mexico, from 1993 to 2019, 2 296 794 ha of RFPs have been established (Figure 6), with over two billion plants (Semarnat, 2020), where INIFAP has generated technology for plant production, establishment and management of plantations and are a reference for planters (Prieto and Sáenz, 2011).

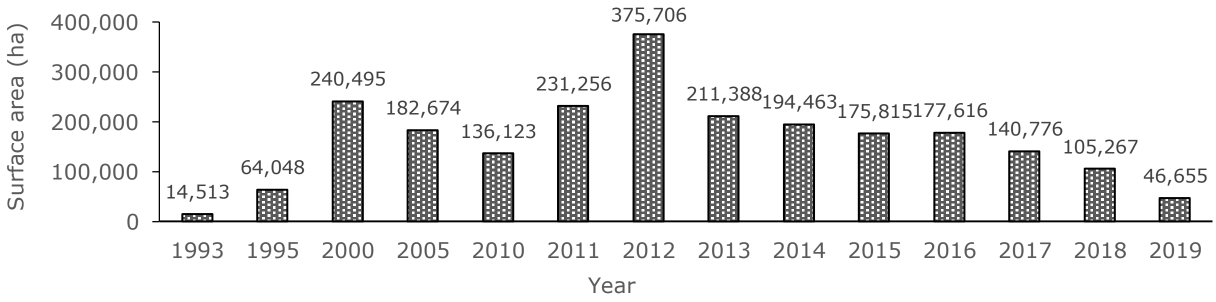

Figure 6. Reforestation areas in recent years in Mexico.

Technology for the production of quality forest seedlings. 26 research papers on 27 species that have had an impact on the forestry sector were located, mainly on seed quality, germination rates and speed, dormancy elimination, plant quality in the nursery, and field survival.

The massive production of quality plants for the establishment of RFPs and CFPs began with the emergence of Conafor in 2000. In this regard, INIFAP has contributed with the generation of technology that has increased plant quality by up to 40 %, and the survival of plantations, by 80 % (Prieto y Sáenz, 2011).

In addition, methods have been developed for the conservation and propagation of priority, recalcitrant, and endemic species. Recalcitrant seeds have limitations for storage and further propagation (Magnitskiy and Plaza, 2007); contrary to what happens with the orthodox ones. INIFAP has conducted 29 studies with 27 species; this has resulted in the storage, for several years, of seeds which naturally lose viability in two to three months, whose subsequent reproduction has also been achieved (Parraguirre and Camacho, 1992) (Figure 7).

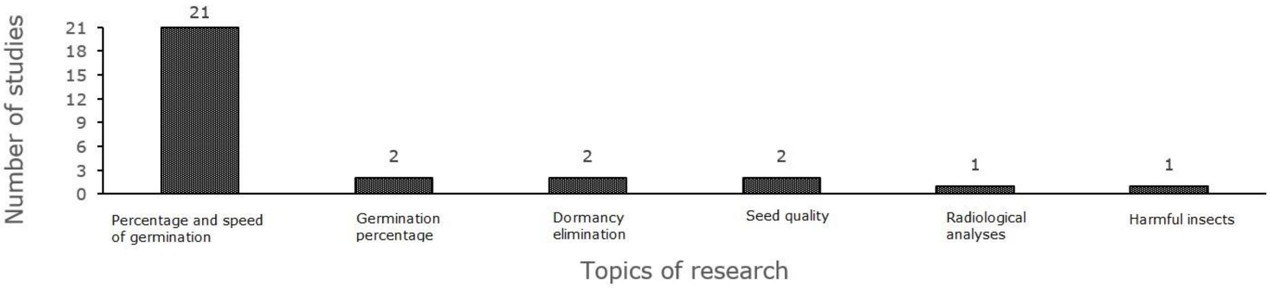

Figure 7. INIFAP's FPP forest plant production issues.

In temperate climates, Camacho (1985; 1987), Camacho and Ramírez (1987) conclude that soaking is the best option to stimulate the germination of *Schinus molle* L. Its seeds can be stored for up to one and a half months, without reduction of germination percentage, and dormancy is eliminated when the seeds are soaked for 24 hours; while, in *Eysenhardia polystachya* (Ortega) Sarg., complete and rapid germination is obtained by separating the pericarp. De la Garza and Nepamuceno (1986) carried out radiological analyses of forest seeds applied in viability control analysis of seeds of different species. Camacho and Molina (1991) determined that stratification and desalination suppress dormancy in *Atriplex canescens* (Pursh)

Nutt., since more than 50 % of ten utricles with seed germinated after being subjected to the above-mentioned treatment.

Bustamante-García *et al*. (2012a; 2012b) studied insects affecting seed set, seed quality, pollination and seed production potential in *Pinus engelmannii* Carr.; their results showed that *Leptoglossus occidentalis* Heidemann is the causal agent of the greatest damage to seed development; Bustamante-García *et al*. (2014) determined the quality and seed potential of *P. durangensis*; obtained averages of 100.3 seeds per cone, of which 73.4 % were full; 53.4 % germinated, and the aborted seeds were damaged by *L. occidentalis* in the early stages of their development. Prieto *et al.* (2014) generated a methodology to determine the quantity and quality of seed in cones, as well as the average daily germination, germination speed, and germination value.

For the tropical climate, Parraguirre and Camacho (1992) established germination rates and speed of germination for 21 species and indicated that the time to achieve 75 % germination is the appropriate indicator for good germination; and Camacho (1994) described seed germination inhibition and techniques to eliminate dormancy, either naturally or by the action of chemical or mechanical treatments.

Technology for the production of quality plants. The success of FPs depends on the quality of nursery-grown plants. In the field, the desired survival rate has not been achieved; thus, from 2013 to 2015, the survival rate averaged 54.2 % (Conafor, 2020). In Mexico, 80 989 872 plants were produced in 154 nurseries between 2018 and 2019 (Conafor, 2020).

INIFAP researchers have published 13 papers on 18 species that support the work of forest nurserymen, mainly regarding plant quality (Figure 8). For example, Prieto *et al.* (2011) evaluated plant quality indicators in 51 forest nurseries in *Chihuahua, Durango, Nayarit, Jalisco, Colima* and *Michoacán*, where, from 2005 to 2009, 43.2 million plants per year^{-1} were produced for the reforestation of 40 016 ha year^{-1}.

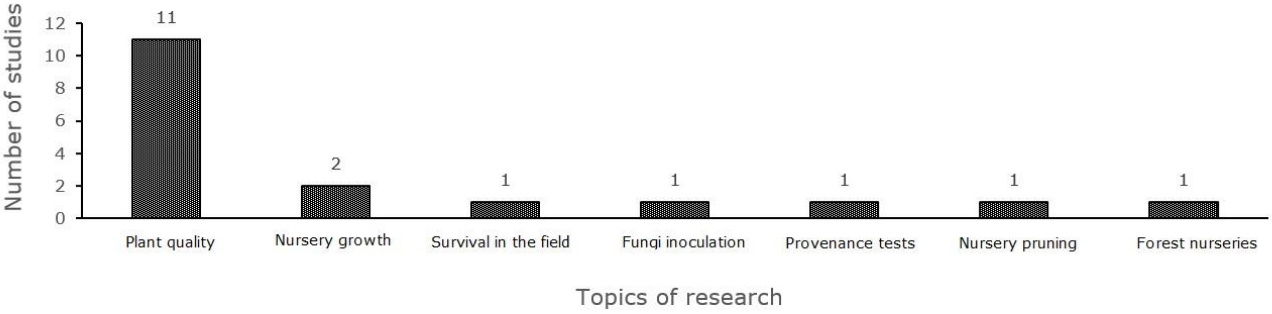

Figure 8. Quality plant production issues in INIFAP's FPP.

In cold temperate climate, Prieto y Sáenz (2011) described the plant quality of hardwood and conifer species in nurseries in five states of the Western *Sierra Madre;* Rueda *et al*. (2012, 2014a) did the same for *Jalisco* and *Nayarit*. These authors indicate that the hardwood and coniferous plants produced are of average quality, according to the standards established in the norm NMX-170-SCFI-2016.

Benavides *et al*. (2011a; 2011b) carried out a nursery diagnosis of the provenances of *P. hartwegii* Lindl. and *Abies religiosa* (Kunth) Schltdl. *et* Cham. from the Neovolcanic Axis, between which no variation was found. Sáenz *et al*. (2014a) determined the plant quality in species of the genus *Pinus*; Muñoz *et al*. (2015a) did the same in conifer taxa, both in *Michoacán*; according to their results, the plants were rated as high quality.

Sigala *et al*. (2015) assessed survival in *P. pseudostrobus* Lindl. plantations; they concluded that diameter is the morphological variable most closely related to the risk of mortality at the plantation sites; Martínez *et al.* (2015) determined the effect of the inoculation of *Russula delica* Fr. on *P. engelmannii* Carr. seedlings; the best results were obtained with irrigation inoculation at a low dose, and the highest percentage of mycorrhization, when the substrate was inoculated at a high dose. Sáenz *et al*. (2017) evaluated the plant quality of *P. pseudostrobus* L. in response to fertilization; they found that the substrate with 2 kg of Osmocote m^{-3} + 5 % compound liquid biofertilizer applied every 30 days led to better results for morphological and physiological variables.

Gómez *et al*. (2017), in *Oaxac*a, when studying the genetic potential in nurseries of *P. greggii* Englem. provenances, observed a differentiated behavior at the variety level; and, in study on their morphological attributes, Pineda *et al*. (2020) registered good quality for *P. greggii*, *P. leiophylla* Schiede ex Schltdl. & Cham., *P. cembroides* Zucc., *P. ayacahuite* Ehren., and *P. hartwegii*. Basave *et al*. (2021) examined the effect of aerial pruning on the morphological quality of *Caesalpinea coriaria* (Jacq.) Willd plants and concluded that its use in nurseries is not recommended.

For the tropical climate, Patiño and Marín (1993) address issues of nursery planning and establishment, production, handling and transport of forest plants, and Patiño *et al*. (1993) propose ways of seed selection, production, plant handling and transportation, site determination, establishment and economic aspects in FPs of *Gmelina arborea* Roxb. and Santiago *et al.* (2015), in *Veracruz*, point out that the use of different substrate mixtures in bags *vs*. containers has a greater influence on the growth of *Hevea brasiliensis*.

Establishment and management of CFPs

Technology for the establishment and management of CFPs. In 2020, Conafor recorded the existence of 230 341 ha of CFPs, 78.4 % of which are located in eight states of the country, and 101 577 ha of agroforestry systems (AS), 77 % of which are distributed among five states (Conafor, 2020). Along this line, 22 papers have been published on 38 commercial forest species; of these, 47.4 % are related to the growth evaluations of the species (Figure 9).

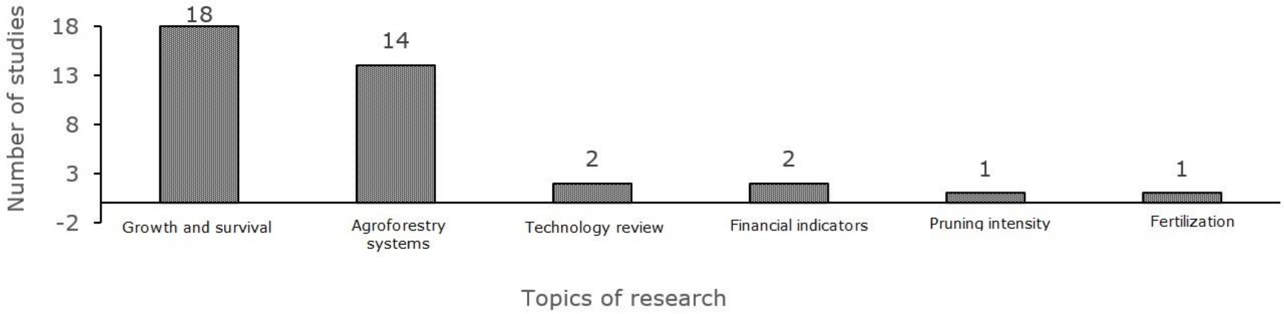

Figure 9. Topics in INIFAP's research line on technology for the establishment and management of CFPs.

Within this context, García *et al*. (2005) tested the effect of pruning intensities on the growth of *Alnus acuminata* spp. *glabrata* (Fernald) Furlow and concluded that pruning at 50 % of the height does not affect height growth, but does affect increase in diameter. Muñoz *et al*. (2009) evaluated the growth and survival of CFPs of *Tectona grandis* L. f., *Acrocarpus fraxinifolius* Wight *et* Arn., and *G. arborea* in *Michoacán*, and they point out that *G. arborea* has potential for CFP development in the dry tropics. In a study on the growth of a mixed plantation in *Veracru*z, Mexico, López *et al*. (2010) register *G. arborea* as the species with the largest increases in all its variables, and, in a mixed plantation of *C. odorata* L.*, Cordia alliodora* (Ruiz & Pav.) Oken*, T. grandis*, and *S. macrophylla*, Hernández *et al.* (2011) cite *T. grandis* as having a superior growth compared to the other three species.

Muñoz *et al*. (2011a) determined the survival and growth of *G. arborea*, *T. grandis*, *Acrocarpus fraxinifolius*, *C. odorata*, and *Eucalyptus camaldulensis* Dehnh. CFPs in *Michoacán*; the authors recommend the ones that obtained the best results based on their productivity. In a research study on growth, survival and phytosanitation in *P. pseudostrobus* Lindl. and *P. greggii* CFPs of the *Purépecha* region, Muñoz *et al.* (2011b) concluded that these species grew in the same way and that their phytosanitary status was healthy in 95.12 % of the cases.

Muñoz *et al.* (2011c) document technology generated for six native and introduced hardwood species; Sáenz *et al*. (2012) compile information on *Pinus* taxa for the generation of their maps of potential areas for CFPs in *Michoacán*, and García *et al.* (2011), in *Quintana Roo*, defined financial indicators for *Swietenia macrophylla* CFPs, which serve producers and funders in the decision-making process.

Likewise, Muñoz *et al.* (2013) studied *T. rosea* and *E. cyclocarpum* FPs in different containers. *T. rosea* in coconut fiber containers showed higher survival than in polystyrene trays; while, for *E. cyclocarpum*, there were no differences between the various types of containers. Sáenz *et al*. (2014b) applied fertilization in *P. pseudostrobus* FPs in *Michoacán*, registered higher increases with compound liquid biofertilizer and the formula of 20 g of 14-07-12 NPK, with values of 27.9 and 16 % higher, with respect to the control. Guzmán and Cruz (2014) determined the growth of *Amphipterygium adstringens* (Schltdl.) Schiede ex Standl. in the field; they conclude that the species shows morphological variation of the fruit and percentages of fruit with a single seed.

In *Puebla,* Muñoz *et al.* (2015b) estimated the growth, survival and phytosanitation in a *Pinus chiapensis* (Martínez) Andresen, *P. greggii* and *P. patula* CFP; they claim that *P. greggii* and *P. patula* have good potential for CBP; in *Durango*, Mejía *et al*. (2015) determined the survival and development of 72 coniferous plantations and point out that in most of them, survival was higher than 60 %, and they could be incorporated into utilization due to their excellent growth. Muñoz-Flores *et al.* (2019) did something similar for *P. pseudostrobus* planted on different dates in *Michoacán*, and they document higher growth and survival of this species when planted at the beginning of the rainy season. Finally, Muñoz *et al*. (2021) in *Michoacá*n evaluated the survival and growth of *Guadua aculeata* Rupr. ex E. Fourn., *G. inermis* Rupr. ex E. Fourn., *G. amplexifolia* Presl., and *G. angustifolia* Kunth; report that *G. inermis* was well adapted to the conditions of the planting site.

Another important issue is that of AS; therefore, Sáenz *et al*. (2014b; 2016) define potential areas for the establishment of silvopastoral systems with pine species and fodder crops; their results confirm the productivity and profitability of *Pinus michoacana* Martínez associated with *Festuca arundinaceae* Schreb. var. *cajun*, applied fertilization in silvopastoral systems with *Pinus devoniana* Lindl. and *Chloris gayana* Kunth, and a silvopastoral system with *P. devoniana* associated with *Avena sativa* L. var. Avemex. Muñoz *et al.* (2014) established AS, all of them in *Michoacán*, Mexico.

Cuevas-Reyes *et al*. (2020) evaluated the profitability of a silvopastoral system of *Leucaena leucocephala* (Lam.) de Wit. associated with *Cynodon dactylon* (L.) Per. Besides, they defined financial indicators and potential areas in order to establish AS, as well as yields and profitability with different forestry and agricultural components, which will be used for decision making by producers.

Growth, incremental and yield models for CFPs. Knowledge of growth and yield through allometric models of trees or stands allows the reconstruction of development, which is basic for the planning of CFP management (Hernández-Ramos *et al.,* 2019). Nine papers have been published on five species, 75 % of which refer to growth curves and site indexes (Figure 10).

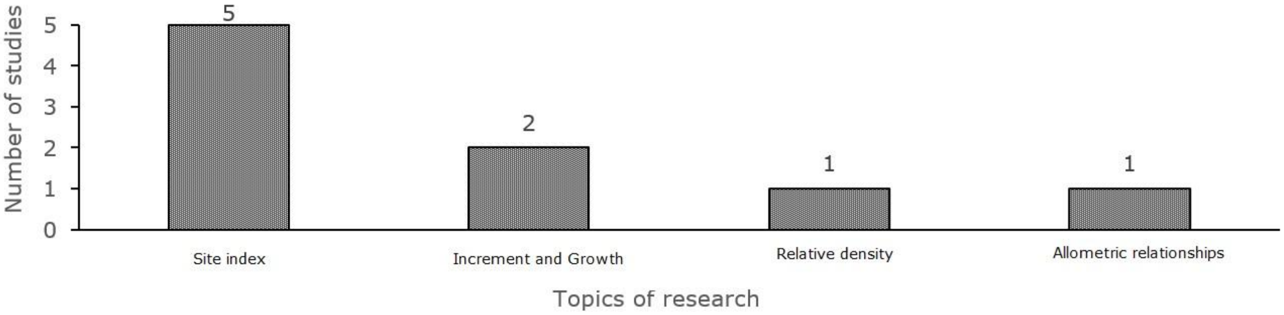

Figure 10. Topics in the line of research concerning growth, increment, and yield models for the CFPs of INIFAP's FPP.

This is an area of opportunity for research development. In this regard, García *et al*. (1992) and García and Rodríguez (2005) modeled height and diameter growth for *S. macrophylla* and *C. odorata*; García *et al*. (1996) developed a density guideline for the management of *S. macrophylla* CFPs. The equations generated have served to define guidelines for the management of the more than 2 500 ha of CFPs of precious species in *Quintana Roo.*

Site Indices (SI) have been proposed to rate CFPs according to the productivity of the site. García *et al*. (1998; 2007; 2021) generated dominant height (*Dh*) equations for *S. macrophylla* and *C. odorata*; Gómez *et al*. (2009) did it for *Eucalyptus grandis* W. Hill ex Maide and *Eucalyptus urophylla* S.T Blake, and Tamarit *et al.* (2014a), for *T. grandis*. Ordaz-Ruíz *et al*. (2020) adjusted allometric equations for *P. patula* CFPs. The equations generated have been used to define the productivity of the soils for the establishment of CFPs of the species mentioned above in *Quintana Roo, Tabasco, Campeche* and the State of Mexico.

Volume and production tables by species. The volume equations, tapering and volume systems allow estimating the actual stock for each tree or part of a tree, and per unit area; at the same time, it is possible to determine the level of reliability of these estimates. INIFAP researchers have published six papers on five forest species (Figure 11); this subject has been little studied, a fact which provides a great opportunity for its development.

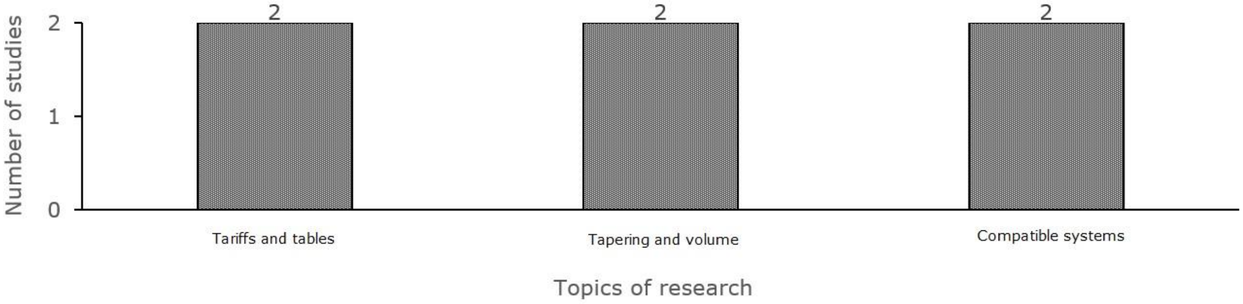

Figure 11. Topics in the line of research related to the tables of **volumes and production** by species of the INIFAP's CFPs.

Within this context, Muñoz (2000) developed tariffs and volume tables for *E. camaldulensis*; Honorato (2011) generated a model for *A. fraxinifolius* that estimates diameters and volumes at different heights; Muñoz *et al*. (2012) adjusted models for volume in *P. greggii* FPs. For their part, Tamarit *et al*. (2014b) constructed a single-tree cubing system, based on a segmented taper function for *T. grandis*; Hernández *et al*. (2017a; 2017b) adjusted compatible taper-volume systems for *P. greggii* and *E. urophylla* CFPs. In the south and southeast, these systems serve to estimate the inventory in 17 500 ha of *T. grandis* and 12 500 ha of *E. urophylla* (Tamarit *et al*., 2014b; Hernández *et al*., 2017a).

Production potential maps for commercial forest plantations. Federal Government promotes a planned forest policy; this requires knowledge of the location of the areas with the greatest potential for each species (Muñoz *et al.*, 2018). INIFAP's scientific staff has published 12 research papers on 32 species of interest, most of them for cold temperate taxa (68.8 %) (Figure 12).

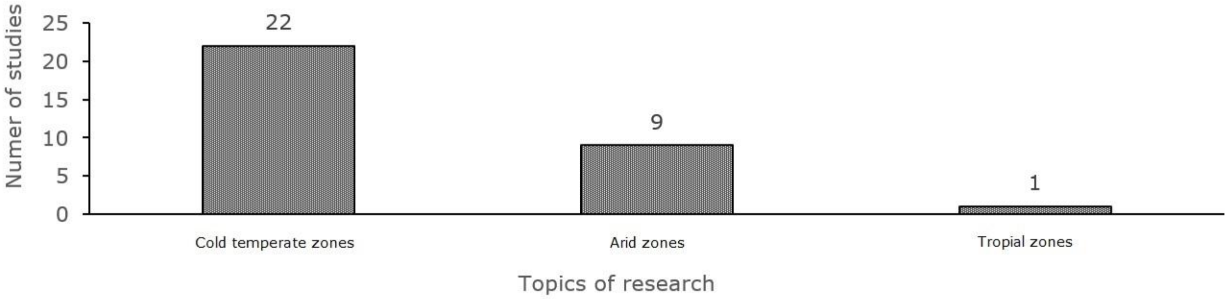

Figure 12. Ecosystems addressed in the research line maps of productive potential for commercial forest plantations of INIFAP’s FPP.

In temperate climate forests, Sáenz *et al*. (2011) conducted the regionalization of potential areas for CFPs in *Michoacán*; in *Jalisco*, Rueda *et al*. (2006) did it for 10 species of *Pinus*, in which *Pinus devoniana* f. *procera* and *Pinus montezumae* Lamb stood out with over 500 mil hectares*;* Muñoz *et al.* (2011d) did something similar for *P. pseudostrobus* and *P. greggii* in Michoacán, and identified surfaces with good potential for CFPs.

Rueda *et al*. (2007) determined potential surface areas for *Pinus tenuifolia* Benth., *Eucalyptus globulus* Labill., *Roseodendron donnell-smithii* Rose, *T. rosea*, *E. cyclocarpum*, and *C. odorata* CFPs in *Jalisco*, and Muñoz *et al.* (2015b; 2016; 2017; 2018) did the same for four *Pinus* species in temperate climate, as well as for *E. cyclocarpum, Tabebuia rosea* (Bertol.) Bertero ex A.DC., and *Brosimum alicastrum* Swarts., in the tropical areas of *Michoacán*.

In tropical areas, Reynoso *et al.* (2016) identify 135 869 ha (17 % of the total surface area) as potential *Agave americana* L. CFPs in *Chiapas*.

In arid zones, Castillo-Quiroz *et al*. (2014a; 2014b) developed maps of areas with a high potential for *A. lechuguilla* CFPs in *Coahuila* and *Tamaulipas*; they estimated a potential surface area of 106 272 ha in *Tamaulipa*s, and of 1 194 877 ha in *Coahuila*. Martínez *et al*. (2015) did likewise for *Lippia berlandieri* Schaurer, *A. lechuguilla* Torr, *Dasylirion* spp., *Agave salmiana* Otto ex Salm.-Dyck ssp. *crassispina* (Trel.) Gentry, *Euphorbia antisyphilitica* Zucc*., Olneya tesota* A. Gray, and *Agave angustifolia* Haw.

The aforementioned works have served as guidelines for producers and institutions to make decisions for the establishment of CFPs (Rueda *et al*. 2006). As a result, a large part of the 230 341 ha of CFPs (Conafor, 2020) has been selected with the support of the maps of areas with productive potential.

Maps showing areas with productive potential for CFPs in the face of climate change scenarios. Identifying conservation areas, refuges and future cultivation zones is fundamental for the conservation of natural resources (Hernández *et al*., 2018). INIFAP's scientific staff has published seven research papers on six species (Figure 13); which indicate changes in the distribution of species under different climate change scenarios.

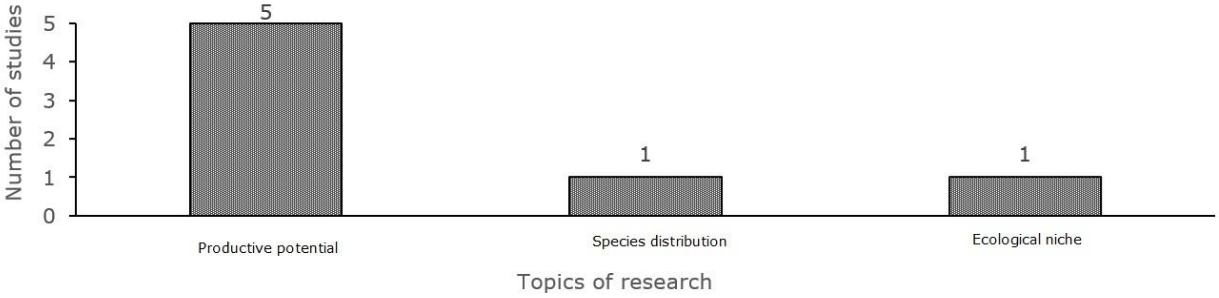

Figure 13. Topics in the research line. Maps with areas of productive potential for CFPS in the face of climate change scenarios of INIFAP's FPP.

In *Jalisco*, Rueda-Sánchez *et al*. (2017) developed maps of current and future CFPs production potential for *C. odorata*, *T. rosea*, and *E. cyclocarpum*; they proved that changes under future scenarios will have consequences for the habitat of the species due to climate change. Rueda *et al*. (2018) did the same for *Pinus maximinoi* H.E. Moore and *R. donnell*-smithii, and they point out that, under the scenarios considered, the distribution areas for the establishment of CBPs will not be significantly affected, as they will decrease by 9 to 12 % with respect to the current optimal areas.

Hernández *et al.* (2018) modeled the historical, current and future distribution under two climate scenarios for *C. odorata*; the authors found that the species has a high probability of experiencing a reduction of its ecological niche in the country. For their part, Reynoso *et al.* (2018) used the concept of ecological niche to generate potential areas for CFPs in the face of climate change effects; the variable of greatest influence for the presence or absence of *P. oocarpa* and *P. pseudostrobus* was the altitude (84.5 % and 97.3 %, respectively). These results delimit the optimal areas for the establishment of Forest Germplasm Producing Units (FGPUs) for the two species.

Indicators of biomass productivity and carbon sequestration in FPs. As a consequence of climate change caused by greenhouse gases, there is a need for carbon sequestration (C) in biomass (B) and soils, and FPs are the option for C sequestration and storage (Acosta *et al.,* 2020). INIFAP has carried out studies on this subject that have resulted in eight publications on 13 forest species, 48 % of which refer to the determination of B and C stocks sequestered in CFPs (Figure 14).

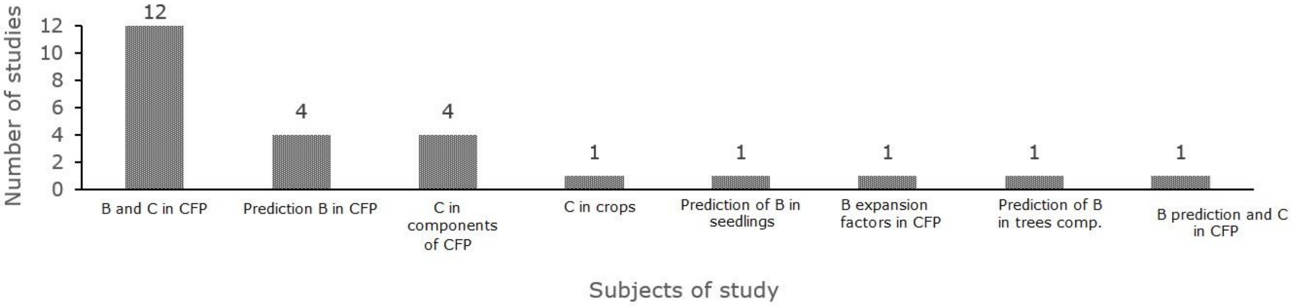

Figure 14. Topics in the research line on biomass productivity indicators and carbon sequestration in the FPs of INIFAP's FPP.

Using the RothC model, González *et al*. (2012) simulated the changes in soil C in corn-squash systems, compared to AS and monocultures with *Ricinus communis* L., and obtained a rate of change of soil organic C (Mg ha^{-1} year^{-1}) of 0.1 to 0.7 after 40 years of simulated land use change with FP of tropical species without management; while, with management, it was -0.2 to 0.3. Rueda *et al*. (2013b; 2014b) estimated B and C in CFPs of eight tropical species and adjusted equations for their prediction; their results indicated that *T. grandis*, and *E. cyclocarpum* had the highest B content and the highest C storage potential; Sigala *et al*. (2016) fitted equations to predict B (aerial, root and total) in *P. pseudostrobus* seedlings under different production systems; their results showed that the diameter was the best predictor variable.

Based on the B stocks, Hernández *et al.* (2017c) generated B expansion factors (BEFs) in *E. urophylla* CFPs. The average EF of total B and the shaft was 510.09 kg m^{-3} and 472.56 kg m^{-3}; furthermore, the conversion factor for stem biomass to total biomass was 1.17. They also estimated a volume of 156.08 m^{3} ha^{-1} and 80 Mg ha^{-1} of aerial B in the evaluated plantation.

In *T. rosea, T. grandis, G. arborea*, and *E. cyclocarpum* CFPs of *Jalisco*, González *et al*. (2018) evaluated the changes in organic C when the land use was changed from agricultural to a FP; they determined that the rate of change in soil organic C (Mg ha^{-1} year^{-1}) after 40 years of simulation with unmanaged plantations was 0.1 to 0.7; whereas, with management, it was -0.2 to 0.3. Acosta *et al.* (2020) determined C in herbaceous plants, shrubs and leaf litter in a mixed FP; the authors pointed out that *E. cyclocarpum* had the highest amount of total C, while *T. grandis* had the lowest content (73.94 Mg ha^{-1} and 45.63 Mg ha^{-1}). In the soil, C decreased by approximately 35 % as depth increased.

Martínez *et al.* (2020) fitted equations to predict B in foliage, branches, stem and root of *P. hartwegii* in RFPs of *Izta-Popo Zoquiapan* National Park and obtained equations as a function of diameter at base. Sáenz *et al*. (2021) estimated B and C in mixed plantations and fitted aerial B models for four tropical species, their results indicated that normal diameter was a good predictor of total dry aerial B of these species. *T. grandis*, *G. arborea*, and *E. cyclocarpum* exhibited the highest biomass content (161, 134, and 130 kg ha^{-1}, respectively) and the highest carbon storage potential (144.6, 120.8, and 117.5 Mg ha^{-1}, respectively). Finally, in *C. odorata* plantations of *Jalisco* and *Colima*, Benavides *et al*. (2021) generated equations for predicting B and C, which exhibited levels of confidence above 97 %.

This shows that FPs are a viable option for C fixation, as they maximize the production of volume per surface area unit and have a high C storage capacity. On the other hand, timber is transformed into durable products; therefore, the fixated C will remain in the structures for long periods of time (González *et al*., 2019).

Conclusions

The published research papers have emphasized the establishment and management of CFPs in the first place, followed by the technology for the production of high quality plants and for agroforestry systems in temperate and tropical ecosystems. Technologies have been generated for determining morphological plant quality parameters for temperate climate and tropical species with an increase of up to 70 % of the field survival rate.

Some areas of opportunity identified from the contributions to knowledge included in the publications considered in this review make reference to growth models, cubic capacity, productive potential under climate change scenarios as supports for the management and selection of areas with potential for the establishment of CFPs.

Most of the published studies deal with evaluations of species that grow in tropical climates, followed by those of cold temperate and arid zones, which implies that certain aspects of the ecology of the taxa of these ecosystems have been neglected.

Conflict of interests

The authors declare no conflict of interest.

Contribution by author

Xavier García-Cuevas, José Trinidad Sáez-Reyes, Hipólito Jesús Muñoz-Flores, Adrián Hernández-Ramos, Agustín Rueda-Sánchez, Jonathan Hernández-Ramos and Gabriela Orozco-Gutiérrez: data collection, and drafting, review, and discussion of the manuscript.

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