DOI: https://doi.org/10.29298/rmcf.v12iEspecial-1.1020

Review article

Investigaciones del INIFAP en manejo forestal y servicios ambientales de bosques templados mexicanos: evolución, logros y perspectivas

Research by INIFAP on forest management and environmental services in Mexican temperate forests: evolution, achievements and perspectives

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Resumen

El aprovechamiento maderable ha sido, históricamente, la actividad económica más relevante en el sector forestal mexicano; aunque la investigación gubernamental en el tema inició después de la creación del Instituto Nacional de Investigaciones Forestales. Recientemente, la generación de servicios ambientales ha surgido como un nuevo campo de investigación. El objetivo fue analizar las aportaciones del Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP) en la investigación científica sobre Manejo y Servicios Ambientales de bosques templados durante los últimos 35 años. Se realizó una revisión exhaustiva de publicaciones científicas nacionales e internacionales arbitradas, en las que investigadores del INIFAP tuvieron una participación relevante. Los resultados se analizaron en tres períodos definidos de desarrollo institucional y en concordancia con la estructura de los sistemas de investigación del INIFAP; en los cuales el Manejo Forestal incluye Biometría, Silvicultura y regímenes de Incendios; y en los Servicios Ambientales se integran: Captura de Carbono, Agua y estudios paleoclimáticos. Se observa un incremento de publicaciones en los dos temas durante el periodo más reciente, atribuible a una mayor disponibilidad de financiamiento a la investigación forestal y a la importancia actual de los bosques en la mitigación del cambio climático. La producción científica se concentró en revistas nacionales, sobresaliendo la revista institucional. La Biometría y Silvicultura son áreas de fortaleza del instituto y corroboran su papel pionero en este tipo de estudios en México; los paleoclimáticos presentan un crecimiento acelerado en el tercer período; en captura de carbono y recarga hídrica el crecimiento es moderado.

Palabras clave: Carbono, biometría, paleoclima, regímenes de incendios, servicios ambientales, silvicultura.

Abstract

Timber production has been historically the most relevant economic activity in the Mexican forestry sector, although governmental research on this matter started well after the creation of the *Instituto Nacional de Investigaciones Forestales* (National Institute of Forest Research). Recently, the generation of environmental services has emerged as a new field in forestry research. The aim of this study was to analyze the contribution of the *Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias* (INIFAP) (National Institute of Forestry, Agriculture and Livestock Research) (INIFAP) to the scientific investigation on forest management and environmental services of temperate forests during the last 35 years. An exhaustive review of forest scientific publications in peer-reviewed national and international journals, in which INIFAP researchers had a relevant participation was conducted. The results were analyzed in three defined periods of institutional development and according with the structure of INIFAP's research programs, where Forest Management includes Biometrics, Silviculture and Fire regimes; while Environmental Services include Carbon Capture, Water and paleoclimatic studies. An increase in publications on the two topics is observed during the most recent period, attributable to a greater availability of financing for forest research and the current importance of forests in mitigating climate change. Scientific production was concentrated in national journals, with the institutional journal standing out. Biometrics and Forestry are areas of strength of the institute and confirm its pioneering role in this type of studies in Mexico. Paleoclimatic studies show accelerated growth in the third period; in carbon capture and hydric recharge, growth is moderate.

Key words: Carbon, biometrics, paleoclimate, fires regimes, environmental services, forestry.

Fecha de recepción/Reception date: 28 de diciembre de 2020
Fecha de Aceptación/Acceptance date: 19 de abril de 2021

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Introduction

Forest research in the Mexican government sector has a relatively short history as the *Instituto Nacional de Investigaciones Forestales* (National Institute of Forest Research) was created in 1958. In this context, research in forest management began with the Department of Forest Management, whose structure was organized to address different aspects of the aforementioned topic (Manzanilla, 1985). Based upon its background and mission, the *Instituto Nacional de Investigaciones Forestales Agrícolas y Pecuarias* (INIFAP) (National Institute of Agricultural and Livestock Forestry Research, INIFAP) has focused on generating knowledge and transferring technologies to improve forest management in Mexico (INIFAP, 2018).

At present, forest ecosystems have gained importance in the face of global phenomena such as climate change, in addition to the incorporation of new visions of the forest such as providing ecosystem services to society through sustainable forest management (Aguirre-Calderón, 2015). Ecosystem or environmental services are defined as "those benefits that the population obtains from ecosystems" (MEA, 2005). Provision, regulation, cultural services and habitat support services have been identified for the temperate forests of Mexico (Galicia and Zarco, 2014).

Traditionally, forest management is considered as the management of natural forest areas for timber production. In this sense, it demands the application of knowledge of Ecology, Silviculture, Biometrics and includes activities aimed at the use, conservation and promotion of forest resources in an orderly manner; in order to satisfy the needs of current and future society (Aguirre-Calderón, 2015). In temperate forests, timber forest use has been favored over ecosystem services, an influence observed in the development of forestry research in Mexico.

On the other hand, there is a need to achieve greater scientific and technological development to increase the competitiveness of the forest sector in the context of policies such as trade liberalization in North America (Álvarez-López *et al*., 2015). Some studies have analyzed the development of forest management (Mendoza and

del Ángel, 1999; Torres-Rojo *et al*., 2016) and environmental services (Torres and Guevara, 2002) in Mexico. The importance of research has also been emphasized to ensure forest management with scientific bases in the face of new national and international scenarios (Von Gadow *et al*., 2004; Aguirre-Calderón, 2015). Therefore, it is clear that scientific research on these issues will continue to face significant challenges in the future.

Given this complex dynamic, it is necessary to analyze the historical role of INIFAP research in Mexico, through scientific contributions in forest management, its magnitude and nature, and environmental services, because until now there is no estimate of them in both disciplines. This information is crucial to understand the impact of research on this knowledge, in addition to providing feedback to the government agencies in charge of promoting this productive activity.

The work described here presents a review of the scientific contributions of INIFAP during the last decades, for which the structure of the institute's research programs on these topics was taken as a reference, and placed in the historical context of the institutional development since its creation. Thus, the proposed objective was to analyze the contributions of INIFAP in scientific research in forest management and environmental services of temperate forests during its first 35 years.

Political and economic context of the forest sector

Forest research at INIFAP is determined by the political context of the country and by Federal Public Administration. Since its creation in 1985 as a Decentralized Administrative Organ, INIFAP became a Decentralized Public Organism, and in 2003 it became a Public Research Center (Urbina, 2017).

In this review, three periods of development of institutional forest research are distinguished: the first covers from 1985 to 2000, the second from 2001 to 2010, and the third from 2011 to 2020. In the 1980s, the forestry sector was administered by the *Secretaría de Agricultura y Ganadería* (SAG) (Ministry of Agriculture and Livestock, SAG)

with a forest policy that promoted timber harvesting and the participation of owners in forest production (Caballero, 2017). With the creation of INIFAP, forest research was integrated into the *Secretaría de Agricultura y Recursos Hidráulicos* (SARH) (Ministry of Agriculture and Hydraulic Resources, SARH), which limited funding that provoked a decrease in the number of scientists and Forest Experimental Stations.

In the last decade of the 20th century, the forest sector was transferred to the *Secretaría de Medio Ambiente, Recursos Naturales y Pesca* (Ministry of the Environment, Natural Resources and Fisheries). At this time, the idea of preserving and improving the environment was strengthened under new legal frameworks. This adjustment influenced forest management since measures were imposed to protect wildlife and other resources to reduce the impact of harvesting (Caballero, 2017). In this period, the project financing scheme in INIFAP changed from having an assigned budget, to the creation of a public-private fund, to more effectively address the problems of agricultural producers, not necessarily foresters.

The second period (2001-2010) coincides with the founding of the *Comisión Nacional Forestal* (*Conafor*) (National Forest Commission, Conafor) in 2001 which promoted a great boost to the sector, both in terms of operations and research. In 2002, the Sectorial Fund for Forestry Research was established, which strongly promoted research at the national level, not only at INIFAP.

In the third period (2010-2020) the trend towards truly sustainable and inclusive forest management has been accentuated by several social and institutional factors. Among them, the acceptance of the role of forests in mitigating climate change. Consequently, INIFAP's forest research has diversified with issues of environmental services, climate effects and disturbance events in forests, without excluding traditional aspects such as timber production. Funding for the institute's forest research has also been expanded with the participation of other sources, in addition to the institution's own resources.

Literature review

An exhaustive review was made of national and international scientific publications with peer-reviewed and authorship of INIFAP researchers, of online documents in the first instance, and in some cases, also of printed material. The main Mexican periodicals in the forest sector are: *Agrociencia* (https://agrociencia-colpos.mx/index.php/agrociencia/about), *Madera y Bosques* (http://myb.ojs.inecol.mx/index. php / myb), *Revista Chapingo Serie Ciencias Forestales y del Ambiente* (https://revistas.chapingo.mx/forestales/?section=articles&subsec=issues) and *Revista Mexicana de Ciencias Forestales* (formerly *Ciencia Forestal en México*) (https://cienciasforestales.inifap.gob.mx/). The search for information covered the period from January 1985 to July 2020. Other national journals were considered when the topic and level of institutional participation in the articles was relevant.

For foreign journals, the search was carried out through the Conricyt platform through the Web of Science site, Scopus, Science Direct, SpringerLink, SciELO, Redalyc and Dialnet, and, as an initial filter, the institutional affiliation of the authors was applied, then the topics of forest management and environmental services.

In all cases, the criteria for incorporating contributions in this review were: a) that the main authors (first, second or correspondence) were active researchers, retired or INIFAP scholars, and b) that the content of the contribution included topics considered in INIFAP about Forest Management and Environmental Services of temperate forests. In other words, forest management covers topics that provide technical-scientific support to different aspects such as: silviculture, management of timber production, fire regimes and biometrics. In the case of environmental services, studies related to carbon quantification, rainfall interception and historical variability of the climate were considered. Due to its relevance in the geographical components of the two scientific areas, studies in Geomatics were also addressed, referring to the digital processing of satellite images and Geographic Information Systems.

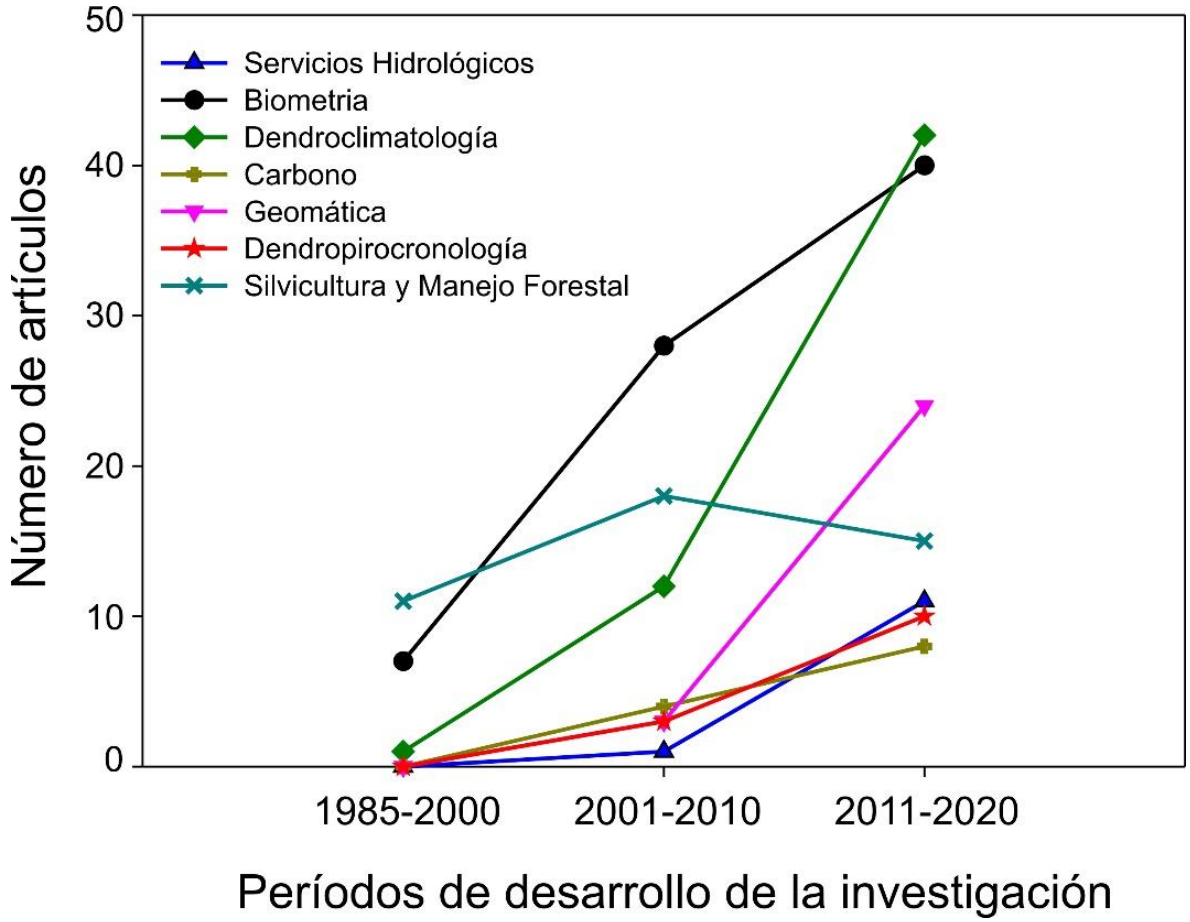
In regard to space limitations, only a representative sample of each topic is mentioned in this document. In the analysis of the information, the periods of institutional

development formerly indicated were highlighted, as well as the type of journals in which the contributions were published. The information was analyzed and plotted with SigmaPlot® Version 10: Exact Graphs for Exact Science software.

Results on research development and achievements

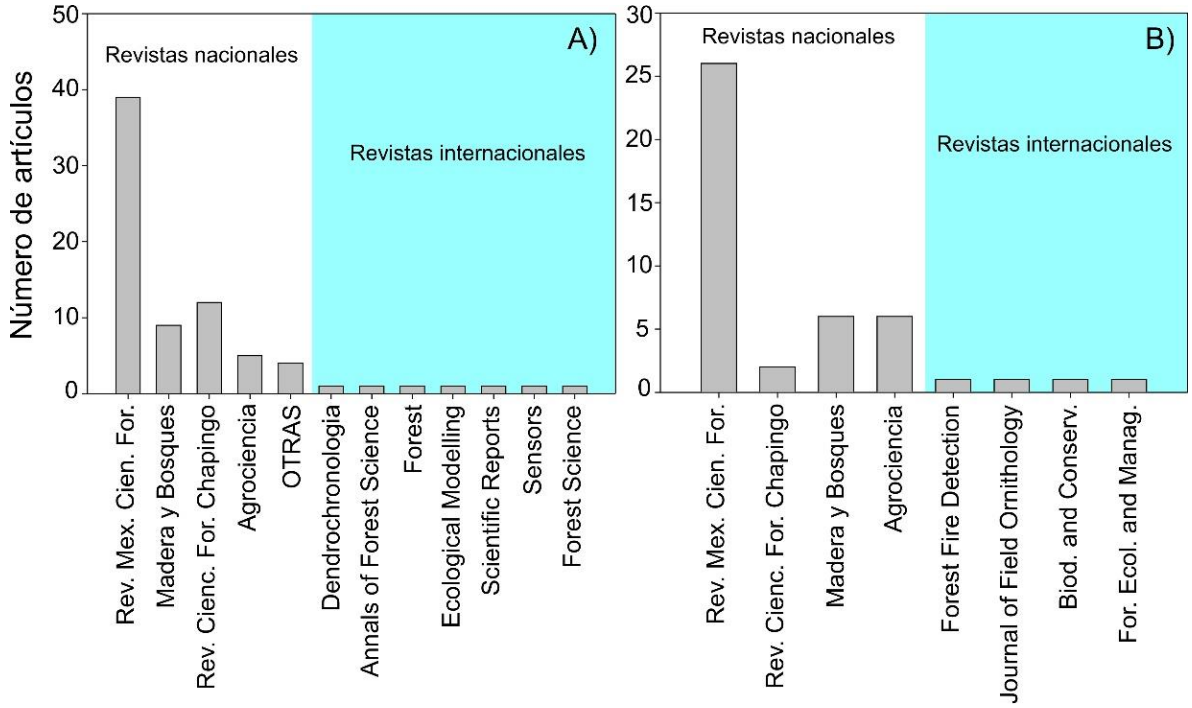
Silviculture and Biometrics

INIFAP studies in this area have been scarce but very important, among which stand out the systems based on regeneration and mortality models in *Pinus arizonica* Engelm forests, in the state of *Chihuahua* (Islas and Mendoza, 1989) focused on restoration, and growth models of *P. montezumae* Lamb., in the state of *Puebla* (Zepeda and Acosta, 2000) with a production approach. These works, essential for decision-making, are notable from the first period on issues of *P. montezumae* seed dispersal (Acosta and Musálem, 1986); regeneration of *P. arizonica* (Chacón and Sánchez, 1986); *Abies religiosa* (Kunth) Schltdl. *et* Cham. (Nieto *et al*., 2003) and of other conifers (Pérez *et al*., 2007). Forest management and forestry investigations were more common in the first two periods (1985-2000 and 2001-2010) and less in the third one (Figure 1), although more diverse, since they include fungal conservation studies (Zamora *et al.,* 2018) and wildlife (Chávez-León, 2019) in areas under forest management. INIFAP's contribution to these issues is better reflected in national journals, mainly in the institutional journal (Figure 2B).



Número de artículos = Number of research papers; *Períodos de desarrollo de la investigación* = Research development periods; *Servicios hidrológicos* = Hydrological services; *Biometría* = Biometrics; *Dendroclimatología* = Dendrochronology; *Carbono* = Carbon; *Geomática* = Geomatics; *Dendropirocronología* = Dendropyrochronology; *Silvicultura y Manejo Forestal* = *Silviculture* and Forest Management.

Figure 1. Trend in INIFAP's scientific production by research topics related to forest management and environmental services during three stages of development.



Número de artículos = Number of research papers; *Revistas nacionales* = National Journals; *Revistas internacionales* = International Journals.

Figure 2. Research papers on biometrics (A) and forest management and forestry (B) developed by INIFAP scientists.

A different trend is observed with biometric studies, which are of great relevance for the development of a more quantitative forestry in Mexico. In these aspects, during the three periods a notable institutional contribution can be observed (Figure 1) in matters of statistical growth modeling, yield and site indexes.

It should be noted that INIFAP has been a pioneer institution in long-term quantitative forestry studies in the country, by developing a methodology and implementing a national network of Permanent Forestry Research Sites (SPIS, for its acronym in Spanish) (Manzanilla, 1985). These were the basis for the first modeling trials of the growth of commercially important conifers in Mexico. In this regard, Mas and Pahua (1989) presented the results of more than two decades of measurements in the state of *Michoacán*; while Martínez *et al.* (2019) made a historical review of the institutional

contribution in the area of forest monitoring through SPIS in northern Mexico. This initiative constitutes the clearest background of a formal long-term monitoring strategy for temperate forests under management in Mexico.

Derived from the above, INIFAP was also a pioneer in site quality studies for *P. montezumae* (Rodríguez *et al.,* 1988), competition indexes in *P. cooperi* C E Blanco (Valles-Gandara *et al*., 1998) and growth prediction and yield of *P. montezumae* (Zepeda and Acosta, 2000) and *P. rudis* Endl. (Magaña *et al.* 2008).

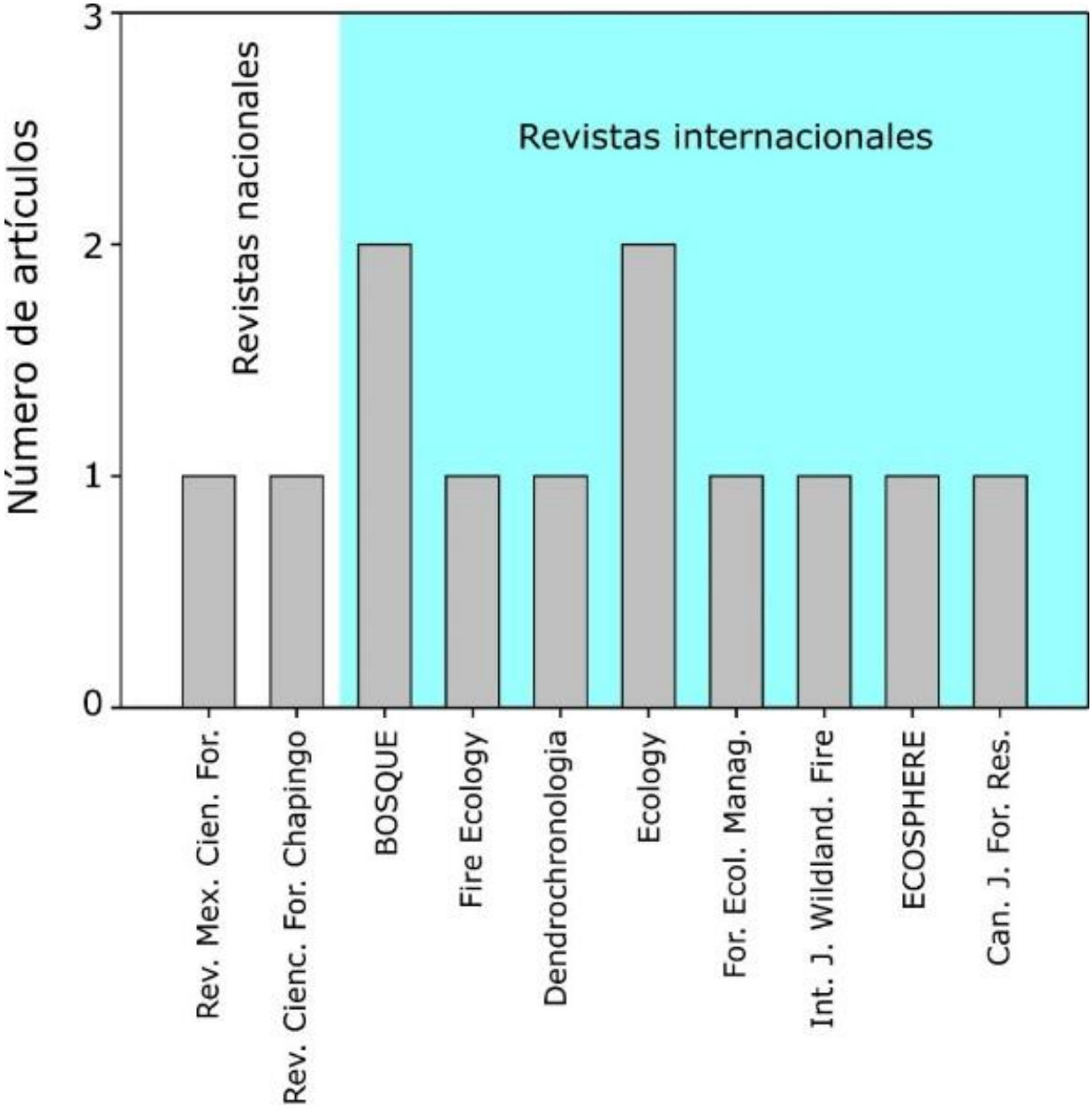
Another relevant aspect is the management of the productive potential of the forests by means of density diagrams. These types of studies in INIFAP are more notable in the third period, with important methodological contributions (Quiñonez-Barraza *et al*., 2018; Quiñonez-Barraza and Ramírez-Maldonado, 2018; Tamarit-Urías *et al*., 2020). Models for estimating the timber volume through compatible taper systems have also been addressed for some species from northern Mexico (Quiñonez-Barraza *et al.,* 2014). In these areas, several works have been published in international journals, although publications in national journals are predominant (Figure 2A).

Fire regimes

One of the ecological factors of great relevance in the management of temperate forests are fires, whose frequency and intensity influence their dynamics (Rodríguez-Trejo and Fulé, 2003). It has been observed that forest management modifies fire regimes due to changes in the structure and composition of forest masses as part of the activities of forest management (Cerano-Paredes *et al.,* 2016). Dendropyrochronological studies allow to establish their frequency, extension, intensity, year and time in which they occurred (Cerano-Paredes *et al.,* 2015). This information is crucial for the prescription of controlled burns and reincorporation of the function of the fire in areas under management.

However, poor knowledge of forest fire regimes has limited its use as a forestry tool. In the last decade, INIFAP has generated a network of studies on fire regimes, thereby

determining the role of meteorological variations in their historical frequency. The records reach at least a century for some regions (Cerano-Paredes *et al*., 2015, 2016) and for others close to 600 years (Cerano-Paredes *et al.,* 2021). This network includes research in Mexico and some localities in *Guatemala*, with the collaboration of national and international institutions, and has been published mainly in international journals (Figure 3). It also stands out that the publications have kept a growing trend since their beginning (Figure 1), the most representative of which are those of Molina-Pérez *et al*. (2016) and Cerano-Paredes *et al.* (2019) in northern Mexico, and Cerano-Paredes *et al.* (2015, 2016) in the center of the country.



Número de artículos = Number of research papers; *Revistas nacionales* = National Journals; *Revistas internacionales* = International Journals.

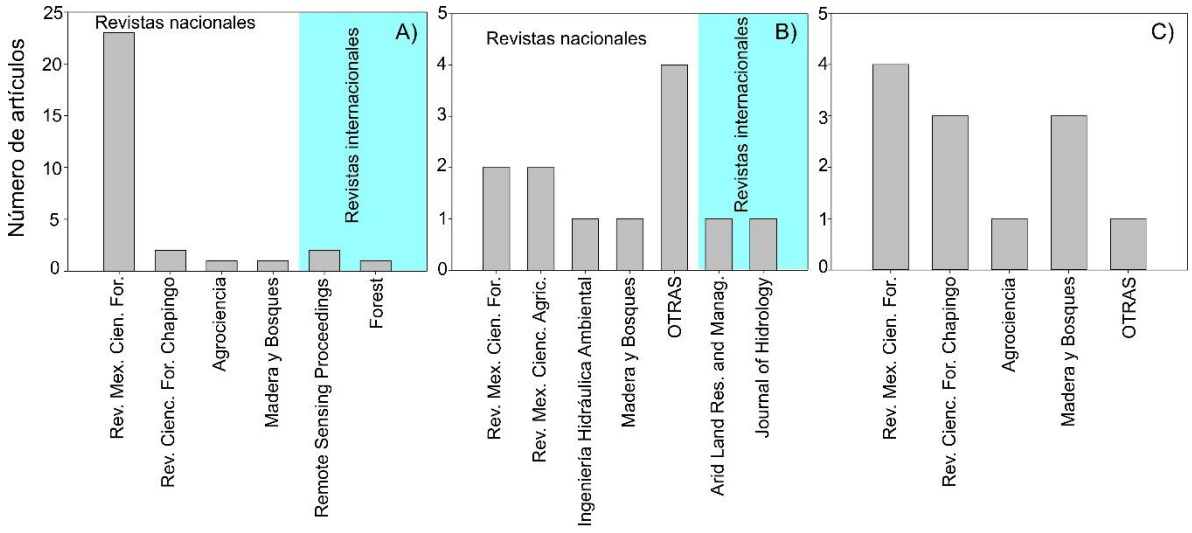
Figure 3. Research work on the reconstruction of fire regimes developed by INIFAP scientists in collaboration with national and international institutions.

These investigations have contributed to the knowledge of (1) the relationship between climate variability and the historical frequency of fires, (2) the influence of general circulation phenomena (*El Niño* Southern Oscillation and the Pacific Decadal Oscillation) in the modulation of extensive and severe fires for different regions of the country, and (3) changes in fire frequency in recent decades attributed to management and suppression. This knowledge is relevant in the current and future context of forest management, considering that it is a long-term activity.

Carbon estimates

Faced with climate change scenarios, carbon capture and storage in forest ecosystems are relevant aspects in programs for the provision of environmental services. The studies that marked the beginning of this line of research at INIFAP emerged in the second period with the generation of allometric equations to determine the biomass and carbon content in different forest species (Acosta *et al*., 2002).

In the current period (from 2011 to 2020) the studies included the integral measurement of carbon in other components of the ecosystem, such as the understory (Acosta *et al.,* 2020) and seedlings (Martínez *et al.,* 2020). Previously, carbon measurement was only included in the aerial part of the trees through allometric models, mainly of cold temperate climate species (Acosta *et al*., 2002; Díaz-Franco *et al*., 2007; Avendaño *et al*., 2009; Carrillo *et al*., 2014). Studies of this type at INIFAP have evolved, albeit at a moderate pace (Figure 1), towards greater diversification in ecosystem approaches and components in the most recent period. The fact that the studies have been published only in national journals stands out (Figure 4C).



Número de artículos = Number of research papers; *Revistas nacionales* = National Journals; *Revistas internacionales* = International Journals.

Figure 4. Research papers on Geomatics (A), hydrological services (B) and carbon (C) generated by INIFAP researchers, published in national and international journals.

Water recharge

Water recharge is another of the environmental services that is increasingly important in forests, since forest cover plays an important role in the water balance in the processes of interception of rain, its infiltration, evaporation and transpiration. Although these issues have been recognized in forests, this line of research started recently at INIFAP in the second period analyzed (Flores *et al.,* 2016), and maintains a growing trend (Figure 1). Most of the publications are in journals whose subject is not only forestry (Figure 4B), which can be attributed to the fact that these processes have causes and effects that are not limited to forests, although they participate in their regulation and provision.

In this sense, INIFAP has carried out infiltration projects, their effect on the recharge of aquifers and the availability of water for plants (López *et al.*, 2016). Likewise, information

has been generated on surface runoff and its relationship with the intensity and volumes of precipitation by types of vegetation cover (Serna and Echavarría, 2002).

Another aspect of interest is the rainfall interception to identify the role of tree cover in the hydrological balance. Interception has been estimated as a function of total rainfall in pine, oak and fir forests (Flores *et al.,* 2016). Muñoz-Villers *et al.* (2012) evaluated processes such as transpiration, evaporation, rain and fog interception.

Paleoclimatic studies

Among the environmental services from forests, climate regulation is perhaps the least evident from a documentary point of view in Mexico. Although some INIFAP studies have shown the effects of forest cover on microclimate variations (González *et al.,* 2015), the understanding of climatological processes on larger scales of time and space is still limited. Global warming will impact the development and management of forests, so the knowledge of the historical variability of the climate is key to understand the role of climate regulation by forests.

In the National Laboratory of Dendrochronology of INIFAP, during the last two periods of this review, studies have been developed that have made it possible to reconstruct the variability of rainfall for several centuries Villanueva *et al*., 2007a; Cerano *et al*., 2009, Cerano, 2011a; Stahle *et al*., 2011; Cerano *et al.*, 2014; Villanueva *et al.*, 2015). Some of these works cover broad geographic scales, based on species such as *Pseudotsuga menziesii* (Mirb.) Franco (Villanueva *et al.,* 2011), *Taxodium mucronatum* Ten. (Villanueva *et al*., 2007b; Stahle *et al.,* 2012) and *Pinus hartwegii* Lindl. (Villanueva *et al*., 2015).

Paleoclimatic studies have also made it possible to reconstruct the occurrence of severe droughts during the last millennium and analyze their impact in the center of the country (Stahle *et al*., 2011). A large part of these studies support the "Drought Atlas for Mexico", which covers the period from 1400 to 2015 (Stahle *et al*., 2016). Likewise, the influence of climatic phenomena of general circulation on the variability of rainfall in the north

(Cerano *et al.,* 2011b; Villanueva *et al.,* 2011) and the center of the country (Cerano *et al*., 2013) has been determined.

Most of the publications on this topic are in national journals, however, there are also several titles in foreign journals (Figure 5) and a faster growth than in any other topic in the present review (Figure 1).

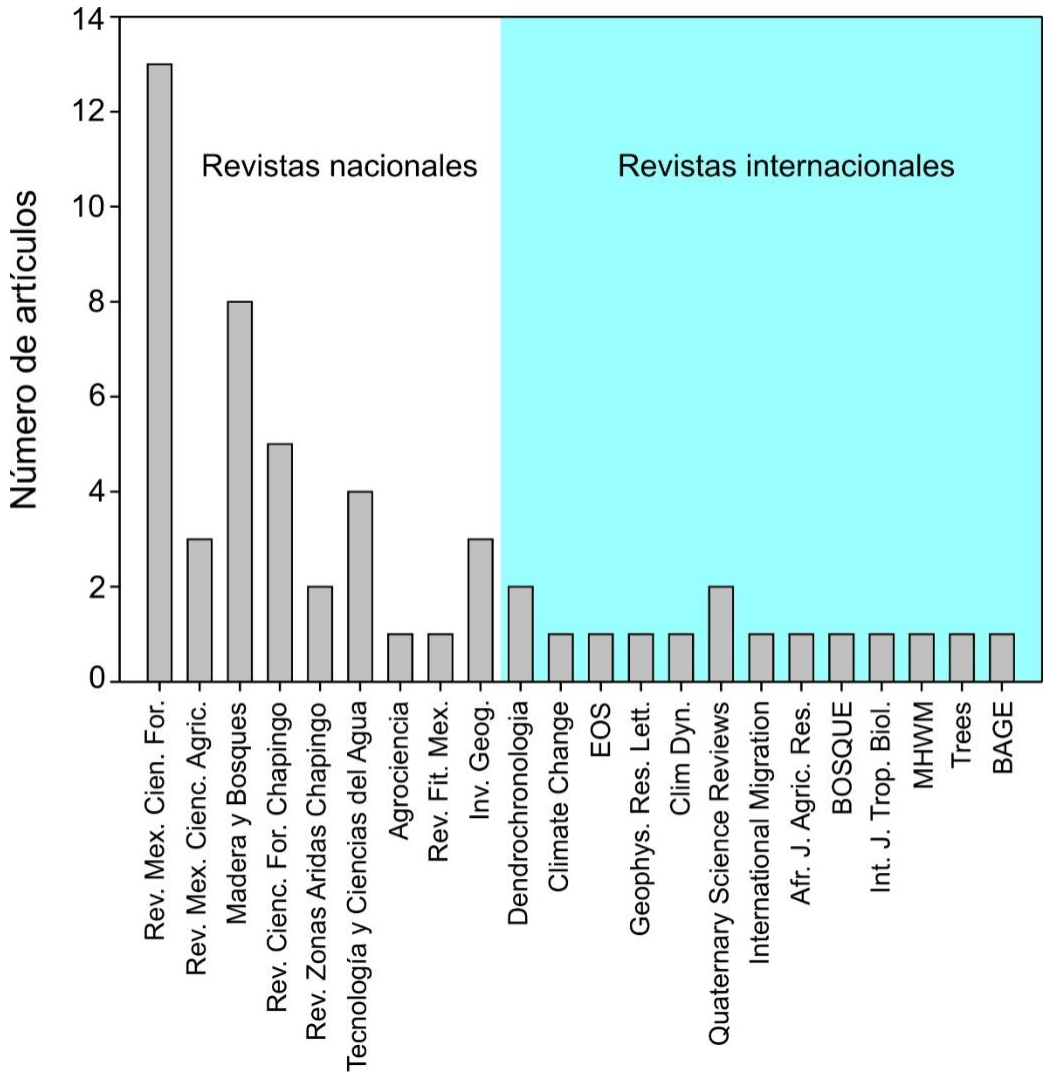


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Figure 5. Research works in Dendroclimatology developed by INIFAP scientists in collaboration with national and international institutions.

Of the different topics analyzed, silviculture shows a slight decrease in the third period. In contrast, Biometrics and Dendroclimatology keep a growing production in the last two. In the evolution of INIFAP, emerging issues such as environmental services show greater development from the second period. In general, institutional changes in the last three decades, as well as the availability of funding, have influenced the recent increase in scientific production in the two aforementioned topics (Figure 1).

Conclusions and Perspectives

Although the research coverage in forest management and environmental services at INIFAP is good, the dynamism of the sector, the technological changes and the national context imply important challenges for institutional research on these two scientific areas.

It is necessary to continue doing research on the forest management and forestry interactions, in order to generate strong bases for decision-making (Monárrez-González *et al*., 2018). The development of models that allow the analysis of multipurpose management alternatives is required, especially in regions where timber production is a preponderant objective. The acquisition of knowledge on forestry systems that favor the simultaneous provision of environmental services in the context of timber production should be promoted. This approach is essential in the face of uncertainty scenarios associated with climate change.

In environmental services such as carbon sequestration, the trend is towards the development of geospatial models to quantify changes in carbon stores derived from vegetation management practices at larger geographic scales. In hydrological services, an important task will be to continue research in the hydrological-forestry field to contribute to forestry decision-making in the context of current payment schemes for environmental services. In regard to dendrochronology, there is a great opportunity to carry out new lines of research with applications in forest and watershed management. Historical fire studies in particular, should guide efforts to support the incorporation of fire regimes as forestry tools. In these perspectives, it is

very likely that INIFAP forestry research will continue to adapt to future changes, to continue generating knowledge and technologies on these two important issues for the advance of the forestry sector in Mexico.

Acknowledgements

The authors express their gratitude to the researchers in the areas of forest management and environmental services, who have contributed with their work to the development and growth of the forest area at INIFAP.

Conflict of interests

The authors declare no conflict of interest.

Contribution by author

Vidal Guerra de la Cruz: design, structure and writing of the article; Enrique Buendía Rodríguez: structure and writing of the article; Julián Cerano Paredes: information processing and writing of the article; Fabián Islas Gutiérrez: structure and writing of the article; José Carlos Monarrez González: review of literature and writing of the article; Eulogio Flores Ayala: review of literature and writing of the article; Tomas Pineda Ojeda: review of literature and writing of the article; Miguel Acosta Mireles: article review.

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