Forest Ecology and Management 524 (2022) 120526

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Forest management practices in Spain: Understanding past trends to better face future challenges

Enric Vadell [a], Jesús Pemán [b], Pieter Johannes Verkerk [c], Maitane Erdozain [d], Sergio de-Miguel [b,d,*]

[a] Ministry of Agriculture, Livestock, Fisheries and Food, Government of Catalonia, Josep Pla, 10 La Seu d'Urgell, 25700 Lleida, Spain
[b] Department of Crop and Forest Sciences, University of Lleida, Alcalde Rovira Roure 191, 25198 Lleida, Spain
[c] European Forest Institute, Yliopistokatu 6B, 80100 Joensuu, Finland
[d] Joint Research Unit CTFC – Agrotecnio – CERCA, 25280 Solsona, Spain

ARTICLE INFO

Keywords:
Forestry
Silviculture
Land use
Forest policy
Indicators
History

ABSTRACT

Because forests provide a myriad of essential services to society, sustainable forest management that considers and promotes the multifunctional role of forests is of key importance. Understanding how forests have been and are being managed is essential to learn how current forest landscapes have been shaped and how management could be improved to better address all societal needs. Spain makes for an interesting case study due to its dramatic expansion in forest cover over the last 150 years following ambitious national reforestation and afforestation initiatives, as well as for its diversity of forest ecosystems and management approaches. However, a national-level assessment of such a development is currently missing. Therefore, our objective was to document and analyse the development of forest management practices in Spain since the mid-20th century. We developed narratives to describe the trends in 11 indicators of forest management decision-making and practices. Results show that while some decisions have evolved towards promoting multifunctionality (e.g., soil cultivation), others have intensified to maximize production at the expense of other ecosystem services (e.g., naturalness of tree species) and others have not changed much during the past 80 years (e.g., type of regeneration). The analysis also showed that some of the indicators have been conditioned by technological innovations (e.g., machine operation) and by the development of certain policies and legislation (e.g., the application of chemical agents). Based on these trends, we identified the main challenges that forest management in general, and in Spain in particular, may face as well as some decisions that may have to be reconsidered (cutting regime, tree maturity, naturalness of tree species) if the country wants to transition towards alternative silvicultural approaches that promote multifunctionality. In addition, a transition towards mixed-species, uneven-aged forests alongside with genetic improvement of tree species would also facilitate rising to one of the main challenges that forest management faces: to develop a climate-smart forestry that contributes to the mitigation of and adaptation to global change.

1. Introduction

Forest ecosystems provide multiple services that societies enjoy and depend upon, including provisioning services (e.g., wood and non-wood forest products), regulating services (e.g., water purification and carbon sequestration), and cultural services (e.g., recreation opportunities and spiritual values) (MEA 2005). Furthermore, forests are key to tackle some of the major challenges humanity faces, such as climate change (UNFCCC 2015) and the biodiversity crisis (UNEP 2010). Forest management, understood as the application of a set of techniques based on scientific knowledge, plays a key role in the supply of these benefits (Hernández-Morcillo et al. 2022). This is because management impacts forest composition and structure, which in turn determine the capacity of forests to deliver ecosystem services (Felipe-Lucia et al. 2018, Schwaiger et al. 2019, Mayer et al. 2020). To ensure the continued provision of these services, forest management needs to pay attention to the different functions of forests beyond the traditional focus on timber provision, and therefore, multifunctional management is gaining momentum in both the scientific literature (Borrass et al. 2017, Martynova et al. 2020) and policy (EC 2013).

* Corresponding author at: Department of Crop and Forest Sciences, University of Lleida, Alcalde Rovira Roure 191, 25198 Lleida, Spain.
E-mail address: sergio.demiguel@udl.cat (S. de-Miguel).

https://doi.org/10.1016/j.foreco.2022.120526
Received 9 July 2022; Received in revised form 1 September 2022; Accepted 5 September 2022
Available online 15 September 2022
0378-1127/© 2022 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC license (http://creativecommons.org/licenses/by-nc/4.0/).

To ensure that this multifunctionality of forests is taken into consideration and incorporated into management practices, first it is important to have a good understanding of how forests are currently managed. Understanding how and why the major decisions in forest management have evolved will help to anticipate and evaluate whether forest management will rise to challenges such as climate change, the biodiversity crisis and divergent societal demands. Although indicators on sustainable forest management have been defined and agreed upon at the European level (e.g., Forest Europe 2020), they tend to represent the effects of forest management (e.g., forest area, structure, damage) rather than the management practices and decisions themselves (e.g., machine operation, choice of forest reproductive materials, types of cutting regimes) that lead to such effects. Hence, how different countries manage their forests in practice is generally poorly documented. Considering how important such management decisions are for the delivery of forest ecosystem services (Sing et al. 2017, Felipe-Lucia et al. 2018), it is crucial to fill this knowledge gap.

Spain is one of those countries in which the role of different forest management practices in landscape modelling and the development of such practices have not been studied in depth at the national level. Previous studies have addressed the topic from other disciplines and perspectives (Mendoza & Olmo 1992, Mendoza & Olmo 2006) focusing on selected regions and without providing a broader, national perspective (Cervera et al. 2015), or have described the development of the result of forest management in terms of changes to the vegetation and landscape in mountainous regions (Serrat & Segura 2003, Antón 2011, Gutiérrez-Hernández et al. 2016). In contrast, the development of forestry practices driving these landscape changes have not been sufficiently studied despite being essential for understanding them.

Spain is a particularly interesting country to study the development and implications of forestry practices, which makes it relevant to an international audience for several reasons. First, Spain stands out within Europe for its great diversity of habitats and forest ecosystems due to its pronounced orography, the presence of four terrestrial biogeographical regions (Mediterranean, Atlantic, Alpine, Macaronesian), the socio-ecological history of the territory as well as the frontier position of Spain with the African continent (Blanco et al. 1997, Rivas-Martinez et al. 2014, IEPBN 2021). Such forest ecosystem diversity has resulted in the development of a wide variety of forest management goals and practices representative of several of those found across Europe. Secondly, although the changes in land use observed in Spain coincide with archetypical patterns and trajectories found across Europe (Levers et al. 2018), the Spanish case is quite unique due to the sharp increase in forest cover experienced in the last 150 years: from 12.5 % of forest area in the mid-19th century (Armenteras 1903) to over 50 % of forest area covering the country nowadays (Álvarez-González et al. 2014). This was partly accomplished due to the development of a national-level policy for large-scale reforestation and afforestation, which resulted in 5.6 million hectares of new forests being established in Spain between 1940 and 2006 (Vadell et al. 2016). Therefore, Spain makes for an interesting case study in terms of forest management and reforestation initiatives.

There is a plethora of valuable information that could help inform current and future forest management within and beyond Spain. However, this information is scattered across various sources of information, and unless properly collated and reported, the opportunity to learn from past experiences to better understand where forest management stands and where it is headed could be lost. Therefore, the objective of this study was to document and analyse the development of forest management decisions in Spain since the mid-20th century. This information enables a better understanding of how forest management has shaped the current landscape in Spain as well as how management could be improved to better address all societal needs towards forests.

2. Materials and methods

2.1. Study area and historical context

The development of forest management in Spain has been closely related to societal and economic changes. Therefore, this section will briefly describe the main changes to contextualize and better understand the results presented in this article.

Forest management in Spain began in 1846 with the creation of the first school of forestry. Up until then, forests were used and harvested based on traditional knowledge and experience that were transmitted from one generation to the next. Like elsewhere in Europe, there were no forestry organisations and professionals yet, and the regulations regarding the use of forest resources were created by local communities with a rather local scope (Tasen 2018). Prior to the industrial development in the 1940s, crop and livestock farming was the main economic activity, and forests were limited to remnant areas where this and other activities were not viable. But the urgent need to halt the process of forest degradation that was occurring due to overgrazing, forest clearing for agriculture and fires prompted the creation of several forest management administrations and policies between 1850 and 1950 (Montero 2018). Several attempts to integrate reforestation into national-level forest planning were made, as for instance the proposals of national reforestation plans of 1911, 1926, 1933 and 1938 (Vadell et al. 2016). These national initiatives aimed to reforest the main basins in the country to address the devastating floods that the country was experiencing as a result of the alarming decrease in vegetation cover.

However, it was not until the second half of the 20th century that forest regeneration efforts in Spain intensified with the creation of a national-level policy on large-scale reforestation and afforestation during Franco's dictatorship (i.e., the period 1939–1975) (Vadell et al., 2016). The National Reforestation Plan of 1938, which concurred with the rural exodus triggered by industrialization, aimed to mitigate the impacts (erosion, floods) of deforestation and forest degradation, to meet the growing demand for timber and energy from emerging industries as well as to boost the economy and tackle the high unemployment rate of rural areas. As a result, 5.6 million hectares of new forests were established between 1940 and 2006 in Spain (Vadell et al. 2016). Hence, forest management became a cornerstone to ensure a stable wood production for the industry sector. The emergence of new materials and fuels and the opening to foreign markets during the second half of the 20th century, however, changed the demand for national wood products (Zavala et al. 2008). Over the last few decades, forest management has evolved to adapt to this changing demand, but also to incorporate the modernization of the forestry sector and to consider the new societal demands from forests such as biodiversity conservation, recreation and climate change mitigation.

2.2. Data collection and analysis

The methodological approach of narratives has been used to present and analyse the development of forest management practices in Spain. Narratives have been shown to be well-suited to reveal trajectories and their underlying causes in the context of land management (Jepsen et al. 2015), so a similar approach has been adopted to describe the development of forest management. To ensure a systematic assessment of the trends, narratives have been structured around the main decisions in forest management as defined by Duncker et al. (2012a) (Table 1).

Due to the scattered nature of the data and knowledge, information on these decisions has been drawn from multiple sources, namely: a) bibliographic reviews (written both in English and Spanish), b) official Spanish data and statistics, c) Spanish and European legislation, d) forest inventories, and e) communication and consultation with national experts and specialists. The Spanish National Forest Inventory data comes from the periodic characterization of permanent plots across the country. There are currently-four editions of the inventory, so their

Table 1
Major decisions involved in forest management and the associated operations, modified from Duncker et al. (2012a).

Decision	Silvicultural operations	Aspects to be considered
Naturalness of tree species composition	Selection of tree species	Species composition in relation to the potential natural vegetation, share of site-adapted tree species, and share of introduced tree species
Type of regeneration	Stand establishment	Natural regeneration, planting, seeding and coppice
Forest reproductive materials	Selection of populations and tree genotypes	Selection of site adapted forest genetic material, use of improved breeding material
Machine operation	Fertilizing, liming, soil preparation, thinning, final harvest	Use of forest machinery for soil preparation, thinning and final harvest
Soil cultivation	Soil preparation, drainage, prescribed burning	Physical site preparation (mechanical and use of prescribed burning) and drainage
Fertilization / Liming	Fertilization, Liming	Fertilization to increase yield (amelioration), compensation for nutrient extraction, and re-establishment of natural biogeochemical cycles
Application of chemical agents	Pest control	Application of pesticides and herbicides
Integration of nature protection	Tree retention, special habitats	Retention of biotope/habitat trees, tolerance of deadwood, and biotope protection within stands
Cutting regimes	Cutting regime of final harvest	Continuous cover, shelterwood, clearcutting, coppice, coppice with standards
Tree maturity	Final harvest	Felling age in relation to the potential lifespan of a given tree species
Wood removal	Thinning, final felling	Tree components (stem, stem tops, branches and stumps) extracted in thinning and harvesting operations

comparison enables to assess the development of forest composition and structure over time (Alberdi et al. 2005, Hernández et al. 2014).

To ensure that the temporal dimension was captured and that the development of the practices over time was described, narratives were divided into three periods: the post-Civil War period (1940–1970), the consolidation of rural depopulation in Spain (1970–1990), and the period when the concept of sustainable forest management became increasingly important through the First Ministerial Conference on the Protection of Forests in Europe in 1990, the Rio de Janeiro Earth Summit in 1992 and the establishment of forest certification schemes (1990-present). Additionally, the changes in the intensity of forest management have been assessed via expert knowledge by semi-quantitatively (using a range of 1 to 5) summarizing how intensively forests have been managed for each of the three study periods.

3. Results

3.1. Naturalness of tree species composition

Native pine trees (*Pinus pinaster, Pinus sylvestris, Pinus halepensis, Pinus nigra*) were the most abundant species during the large-scale reforestation conducted by the public administration during the first period (1940–1970) (Vadell et al. 2019). These native species, which made up 77 % of the reforested area, corresponded to successional stages rather than the potential or climax vegetation in most sites. However, the use of fast-growing exotic species started to gain momentum during this period, with ~15 % of the reforested land corresponding to these species. *Pinus radiata* (107,000 ha) and *Eucalyptus* spp. (164,000 ha) were the dominant exotic species, which showed good adaptation and growth in the tests that private owners conducted since the mid-19th century. In addition to *P. radiata* and *E. globulus*, the exotic species *Pseudotsuga menziesii*, *Quercus rubra*, *Larix europea* and *L. leptolepis* were also planted in northern Spain, whereas *Populus* × *euramericana* and *Eucalyptus camaldulensis* were used in more Mediterranean areas.

During the second period (1970–1990), the use of *Quercus* species such as *Q. robur* and *Q. suber* started to increase (especially at the end of the period), which represented the natural optimum (climax) vegetation in many areas (Vadell et al. 2019). Similarly, there was an increased interest in the use of mixed stands of native species (especially in ecosystem protection stands) as opposed to the preference for monospecific stands that dominated the previous period. Many agricultural lands abandoned during the rural exodus were colonized by pioneer species such as native pines (mainly *Pinus halepensis, Pinus sylvestris and Pinus nigra*). This, together with the large-scale reforestation of Spain, explains part of the species composition that the country has today (Fig. 1).

Regarding the third period (>1990), the main trends in species composition as described in Vadell et al. (2019) were: 1) a slight increase in the share of plantations (from 8.2 % to 10 % of the forests in 1990 and 2010, respectively), with most planted stands being composed of exotic fast-growing species such as *E. globulus*, *E. nitens*, *Pinus radiata* and *Populus* hybrids; 2) the widespread use of native oak species (namely *Q. ilex* and *Q. suber*) within the framework of the European Union's Programme for the Afforestation of Agricultural Land established in 1993; 3) the promotion of species mixtures (mixing different coniferous species, different broadleaved species, as well as coniferous and hardwood species), such as the combination of species of the genera *Sorbus*, *Acer* or *Fraxinus* with other conifers or hardwoods; 4) an increased interest in species that produce high-quality timber, namely *Juglans* spp. and *Prunus avium*, but also *Fraxinus excelsior*, *Sorbus torminalis*, *Alnus glutinosa* and *Betula* spp; and 5) an increased use of shrub species in afforestation such as *Chamaerops humilis*, *Crataegus monogyna*, *Juniperus oxycedrus*, *Juniperus phoenicea*, *Pistacea lentiscus*, *Rosmarinus officinalis* and *Spartium junceum* (Vadell et al. 2016). As a result of all these trends, the most abundant species at present correspond to native species, with the native oak *Q. ilex* being the most widespread species (covering % 14.2 of the woodland area) followed by the native pine *P. halepensis* (% 11.2).

3.2. Type of regeneration

Forest management during the first period (<1970) applied different methods of regeneration depending on the tree species (Artigas 1890, Madariaga 1909, Navarro-Garnica 1977). Natural regeneration was the preferred method in semi-natural stands of native conifers. Coppice regeneration was used for *Quercus* species (especially *Q. ilex*, *Q. pyrenaica* and *Q. faginea*) to obtain firewood and charcoal, for *Fagus sylvatica* to produce firewood, as well as for *Castanea sativa* to obtain carpentry and stake material. Exotic fast-growing species for sawn timber were usually artificially planted following final clearcuts, whereas eucalypts were coppiced. Planting was also the regeneration method used in most reforestations, preferably using bare root seedlings. Finally, sowing tended to be the preferred regeneration method for *Pinus pinaster* and *P. pinea*. Although sowing was also used to some extent for *Quercus ilex*, the massive seed losses due to consumption by wild boar (*Sus scrofa*) led to the abandonment of this regeneration method.

After the 1970s, the planting of seedlings became the preferred regeneration method over sowing (Molina et al. 1989, Serrada 2000). Container-grown seedlings (as opposed to bare-root seedlings) increased during this period as they performed better in the arid conditions of the Mediterranean region. Towards the end of the 1980s, the abandonment

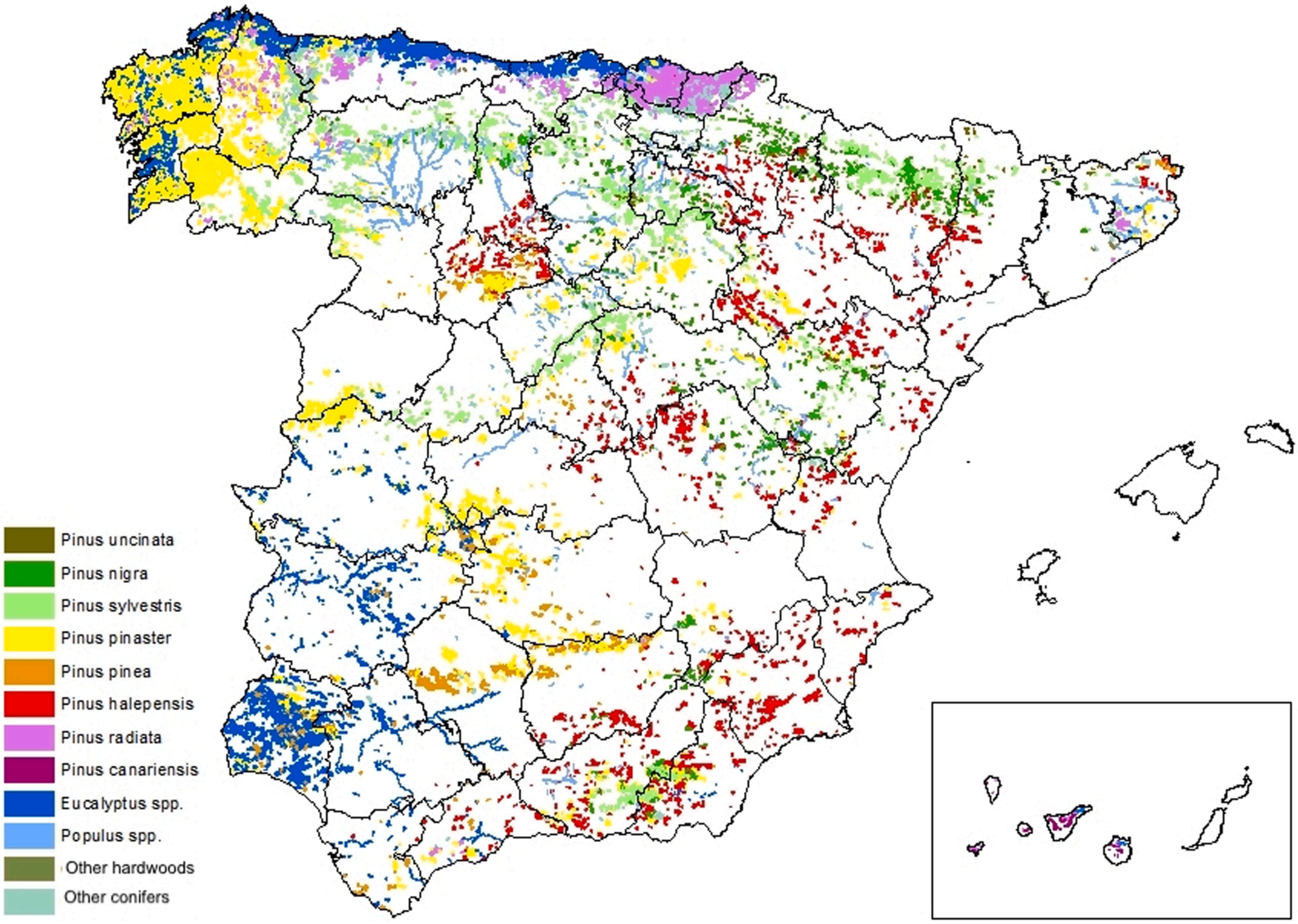

Fig. 1. Forest area originating from reforestation according to the dominant tree species in 1997 (Vadell et al. 2019).

of the worst *Quercus* coppice stands began due to the waning interest in firewood production.

During the last period (>1990), natural regeneration remained the preferred method when managing natural stands of native conifers (namely, *Pinus* spp) (Navarro Cerrillo et al. 2021). The best stands of *Quercus* species (especially, *Q. ilex*, *Q. pyrenaica* and *Q. faginea*) continued to be coppiced for firewood and charcoal, but some were converted into sown stands to improve genetic diversity. Another case of change in the type of regeneration during this period is that of some resprouting species (*Populus* spp., *Eucalyptus* spp., *Pawlonia* spp., *Salix* spp.). The increased interest in energy crops resulted in the replacement of the traditional regeneration method used for these species when the aim was timber production by short-rotation (2–3 years) coppices aiming at biomass production.

Regarding afforestation/reforestation, planting (as opposed to sowing) has been the most common method during the last period (Navarro Cerrillo et al. 2021). In dehesas (agro-sylvopastoral systems), densification is conducted to assist the otherwise difficult regeneration due to the presence of cattle. In natural/artificial stands of *Pinus* spp., enrichment planting with hardwood species is currently frequent to accelerate natural succession and increase biodiversity, especially when the goal of the reforestations was protective. Sowing is limited to certain stands reforested with Mediterranean species of the genus *Quercus*; shelters are used to prevent damage by birds and rodents. Aerial pine seeding for the restoration of burned areas has also been experimentally tested during this period. An aerial seeding trial after a wildfire in Catalonia (northeastern Spain) in 1994 achieved a germination rate of 5 % (Castell and Castelló 1996).

3.3. Forest reproductive materials (FRMs)

After the Civil War, the origin and production of FRMs was national, and the improvement was scarce. The first improvement attempts focused on *Populus* spp. and consisted in selection and hybridization. The clones considered of greatest interest in Europe were imported, and the possibility of using native species (*Populus alba*, *P. nigra* and *P. tremula*) and their natural hybrids was also explored. FRMs (i.e., seeds and seedlings) were initially imported from the Netherlands, Italy, France, Germany and Morocco; seeds of *Populus deltoides*, *P. angustifolia* and *P. tremuloides* were also imported from the US and Canada.

The 1980s saw significant developments in terms of FRM such as: the establishment of the tree breeding and genetic improvement programme for *Pinus pinaster;* the creation of clonal seed orchards for the genus *Pinus* (Alia et al. 1991, Arregui & Merlo 2008); the beginning of the breeding programme for *Pinus radiata* in the Basque Country and Galicia, which intensified in the 1990s (Arregui et al. 1999; Sampedro 2006); the selection of breeding material for *Eucalyptus globulus*; and the beginning of the breeding programme for selecting elms resistant to the Dutch elm disease because of the extensive and serious impact of this disease on *Ulmus minor* stands. The latter programme was further developed throughout the 1990s and produced elm FRMs resistant to the disease. The genetic improvement of *Populus*, on the other hand, slowed down during this period; yet, Italian (Luisa Avanzo, I-MC, Triplo), Dutch (Flevo) and American (Agathe) clones were introduced. During this period, the National Catalogue of Basic Materials for obtaining FRMs was created and specified which materials were authorized for commercialization (except for eucalypts).

The entry of Spain in the EEC in 1986 led to the incorporation of

European policies concerning the commercialization of FRM into the Spanish legislation. In 1994, Spain joined EUFORGEN, an international cooperation programme that promotes the conservation and sustainable use of forest genetic resources in Europe as an integral part of sustainable forest management. Since the 1990s, new basic materials have been approved and incorporated into the Spanish National Catalogue of Basic Materials as a result of the different tree breeding and genetic improvement programmes. The main programmes include clonal or seedling seed orchards for the genus *Pinus*, breeding programmes for *Pinus radiata* in the north, and selection of breeding material from individuals with the most suitable phenotype for *Juglans regia, Prunus avium, Acer pseudoplatanus* and *Betula* spp. Currently, there is a total of 532 basic materials within the "selected", "qualified" and "tested" categories as defined by the Directive 1999/105/EC, and none of them is a genetically modified organism. The production of FRMs has decreased over the last 10 years in terms of seeds and seedlings but has remained constant (or even increased) for cuttings/stakes (Fig. 2).

3.4. Machine operation

Forest management became increasingly mechanized (Table 2), with this mechanization starting in the 1950s partly as a result of the economic agreements signed with the US in 1953. Machines such as crawler tractors, terrain vehicles and planting machines and augers were provided to Spain by the US. Concerns about the impact of some machines started to be raised in the 1980s. For example, concerns about the impact of terraces on soils and landscapes led to the design of high-stability articulated tractor prototypes (TRAMET and TTAE) in Spain. Unfortunately, their high economic cost and low resistance to harsh working conditions did not make them operational.

3.5. Soil cultivation

The main objective of soil preparation for reforestation purposes in the Mediterranean area of Spain was to improve the physical properties of the soil (namely porosity) to facilitate the development of roots and water infiltration (Serrada et al. 2005). During the first period (1940–1970), the general recommendation was for soil preparation to be intense in terms of depth (60 cm) and area. Because the land where reforestation was conducted had often steep slopes and degraded soils, soil preparation was done in rows following the level curves and conserving the vegetation between the rows to minimize erosion. On steep slopes (>35 %), the most common soil preparation techniques were manual hoeing (40 × 40 × 40 cm holes) or tillage with animal traction (oxen with a Brabant plough). With the introduction of chain tractors, oxen were no longer used, and the subsoiling started to be done using rippers. On less steep terrains (<10–15 %), soil preparation was done on the entire area by tillage with agricultural/farm tractors and mouldboard ploughs. The drawback of this preparation method was the inversion of topsoil horizons.

During the 1970s, similar soil preparation procedures were used: tilling (angledozer + mold plough), subsoiling or ridging (angledozer + ripper) for slopes < 35 %, and terraces (tiltdozer + ripper) for slopes ranging from 35 % to 60 % (Pemán & Arnó 1998). In the humid areas of northern Spain, prescribed burning was allowed. Holes, which in the previous period were done manually, started to be done using

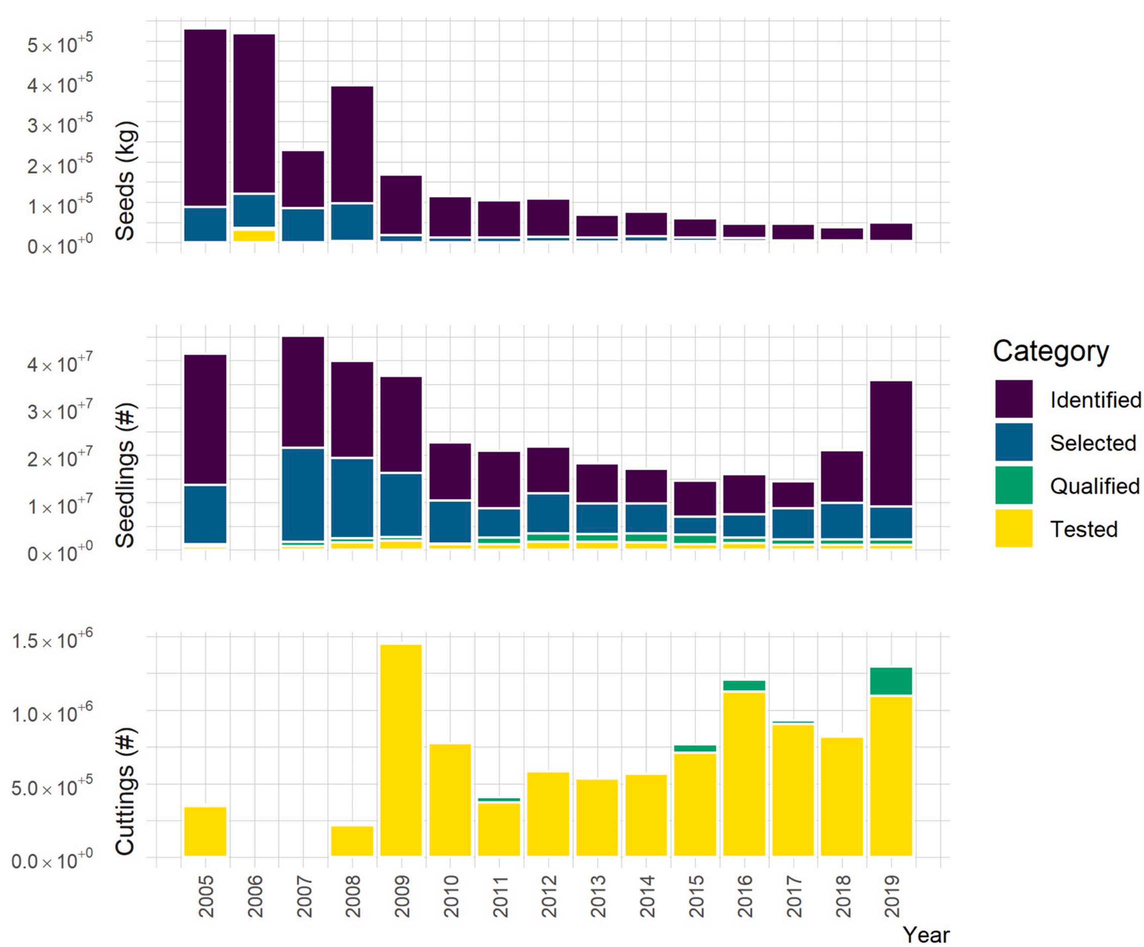

Fig. 2. Development of the production of forest reproductive materials (panels: seeds, seedlings and cuttings) and their category (colours/shapes: identified, selected, qualified or tested) between 2005 and 2019. (Source: MITECO 2021).

Table 2
The development of machine operation in different forestry practices.

	1940–1970	1970–1990	>1990
Clearing and soil preparation	1940s and 50s: manual or animal traction (oxen). End of 50s: beginning of mechanization (bulldozers).	Mostly mechanized. Manual became rare.	Spider/walking excavators (slope > 35 %). Brush cutters coupled to agricultural tractors or caterpillars.Stump grinders (Populus spp. plantations). .
Reforestation and planting	Beginning of mechanization: crawler tractors, terrain vehicles, planting machines and augers. Manual earth augers.Chain tractors for subsoiled terraces (end of the period). .	Angledozers and tiltdozers.	Manual planting mostly.
Felling	Axe (diameter < 12 cm). Chainsaw (>12 cm).	Chainsaw.Harvesters, skidders and forwarders (big forestry companies for plantations with fast-growing species). .	Chainsaw.Harvester heads and feller-buncher heads increasingly more frequent (the latter for bioenergy). .
Debranching and debarking	Axe. Chainsaw (at the end of the period). .	Portable chippers. Debarking mostly in the factory.	Portable chippers (due to the increasing interest in forest biomass for bioenergy purposes).
Hauling	Mules and oxen (small trees). Tractors (larger trees). .	Experiences with aerial cables (low economic profitability prevented consolidation).	Dragging cable (usually pulling with an agricultural tractor). Skidder use is increasing.Forwarders (when harvesting heads are used). . Animal traction only in remote mountain areas. Aerial cable rather experimentally in natural protected areas.
Transportation	Trucks had no crane, complicated. Cable cranes in some areas.	Trucks with cranes.	Trucks with cranes.

excavators. In the 1980s, terraces were no longer used on > 35 % slopes due to their impact on the soil and landscape; instead, holes were dug using a modified ripper that was carried by a chain tractor that moved along the line of maximum slope. The practice of draining certain endorheic wetlands was abandoned due to the high ecological value of these areas. In protective reforestation in arid and semi-arid climates with steep slopes and torrential rains, the micro-catchment technique has been used, which considerably increases the availability of water for the seedlings. Tillage was common to favour natural regeneration and seed germination in clearcut conifer stands.

Since the 1990s, as a consequence of the generalized use of the spider/walking excavators on slopes > 35 %, the most common soil cultivation technique in reforestation is that of digging holes; terracing is no longer used (Bocio et al. 2004). For slopes < 35 %, tilling, subsoiling or ridging remained the most commonly applied methods. In much of the degraded lands in the Mediterranean area, slow-liberation fertilizers and hydrogels are being experimentally applied to improve the moisture content of the soil. Similarly, organic amendments from either urban solid wastes or sewage sludges are being experimentally used to improve degraded soils prior to reforestation. Irrigation is frequently used in *Populus* spp., *Juglans* spp. or *Prunus avium* plantations as well as in plantations for truffle cultivation due to the long summer drought period of the Mediterranean climate.

3.6. Fertilization / liming

During the 1940 – 1970s, no fertilization was applied. The only remarkable exception was liming in *Populus* sp. plantations, which were often subject to river floods that brought nutrients. The first experimental trials with fertilization of fast-growing species started during this period, but fertilizer use in forestry was uncommon.

In the 1970s, fertilizers (3–6 compressed forest manure tablets) started to be applied during the planting of fast-growing species in some acid soils of northern Spain. There were some variations in composition (i.e., NPK 11-18-11 or 8-8-16) and the studies on the pattern of nutrient release and leachate showed that around 80 % of the initial N, P and K contents were lost after 1.5 years equivalent of rainfall. Although research conducted at that time showed positive effects on stand growth (e.g., a 25–76 % increase in wood production in *Eucalyptus* plantations; Viera et al. 2016), the relatively high cost of application and the difficulty in reaching a high enough dose per plant limited fertilizer use.

Since the 1990s, fertilization became a more widespread practice in planted stands, partly due to the impulse to reforestation and forest plantations given by the Programme for the Afforestation of Agricultural Land since 1993. As a result, some eucalyptus, Monterrey pine, Maritime pine and Douglas fir plantations in northwestern Spain started to be fertilized upon establishment with low doses. The effect was short-lived due to the quick leaching associated with humid climatic conditions in that region. It is estimated that ∼ 1,000–1,500 ha of new eucalypt plantations are created and fertilized every year in that area of Spain (Galicia) through the governmental subsidies that support the application of slow-release fertilizers at the establishment stage. In the absence of subsidies, private owners tend to prefer fast-release, soluble fertilizers. There is practically no use of maintenance fertilizers during stand development even though some experts recommend it. Fertilization practices differ between non-industrial owners and pulp companies, with fertilization being more intensive with the latter (Viera et al. 2016).

The composition and concentration of the fertilizers shifted from 2000 onwards based on the results obtained in the 1990s. Forest owners initially applied fertilizers that were made for agricultural purposes (i.e., NPK 15–15–15), but because there is no N shortage in the soils of northern Spain, these treatments resulted in the unbalanced development of the aboveground tree biomass compared to the root system as well as an increase in fungal diseases in *P. radiata* plantations. Therefore, from 2000 onwards, the composition of the fertilizers for these plantations changed to NPK 0-18-0, 0-21-0 or 0-27-0 (so-called superphosphates), with very sporadic supply of magnesium and/or calcium. Fertilizers are applied at the plantation establishment stage and right after the first, second and even the third clearing/thinning usually conducted at stand ages of 5, 8 and 12 years, respectively. Currently, the forest administration subsidizes voluntary soil analyses to advice forest owners on the most suitable dose and composition of fertilization treatments. Several studies recommend fertilizing *P. radiata* plantations as a common practice due to the lack of P and Mg in NW Spain (Sánchez-Rodrıguez et al. 2002, Zas 2003). Eucalypt plantations in the same region of Spain tend to be fertilized with fast-release NPK 8-24-16 fertilizers at the establishment stage and, sometimes, also right before eucalypts start to re-sprout after the final cut. Poplar plantations are seldom fertilized as the marginal gains in tree growth and wood production do not compensate for the fertilization cost. Such plantations are mostly placed in lowlands and alluvial plains and, therefore, their growth is not usually limited by lack of water or nutrients.

3.7. Application of chemical agents

The most used insecticides until the 1970s belonged to the group of organochlorines, among which DDT (dichloro diphenyl trichloroethane), HCH (hexachlorocyclohexane) and Lindane were the most common ones. The method of application was either ground-based spraying (in *peri*-urban or urban areas) or aerial spraying (in forested areas), with the first aerial spraying in Spain taking place in 1950 (Albaladejo et al. 2016). Powder particles ranged between 10 and 15 μm and provided a large coating. The formulations and doses used were 10 % and 20 kg/ha for DDT and HCH, and 1 % for Lindane. By the end of this historical period, 300–400 thousand hectares were being treated per year. Biological control treatments started to be implemented at the end of this period by increasing the abundance of natural predators of certain pests such as insectivorous birds (*Parus* spp.), red ants (*Formica rufa*, *F. lugubris*, *F. aquilonia*, etc.) or bats (*Myotis* spp., *Rhinolophus* spp., *Pipistrellus* spp.).

Between the 1970-1990s, in addition to the organochlorine insecticides that were still used (except for DDT which was banned in 1977), organophosphate insecticides such as Malathion and growth-inhibiting insecticides that interfere with the formation of chitin such as diflubenzuron started to be used. The novelty during this historical period lies in the development of equipment that allowed for the application of ultra-low volume (ULV) treatments. This was the most used method in aerial treatments, with doses ranging between 5 and 10 l/ha (formulations had to be liquid for this equipment). At the end of the 70s, trials on the pine processionary (*Thaumatopoea pityocampa*) were conducted and started to be used at a large scale (Robredo 1980); later expanded to other defoliating pests such as *Lymantria dispar*. At the end of this stage, microbiological insecticides based on *Bacillus thuringiensis* started to be applied using ULV techniques, especially against the processionary. Several fungicides were also used during this period: the Bordeaux mixture ($Ca(OH)_2$) as a preventive treatment (1 or 2 % concentration sprays), copper oxychloride or cuprous oxide for seed treatment, potassium sulfide as a curative treatment, sodium pentachlorophenate and lindane to treat round logs and sodium pentachlorophenate to treat sawn wood, and benomyl to protect cork oaks from *Botryosphaeria* (which causes the chancre disease and depreciates the value of the cork).

In 1986 (year in which Spain entered the European Economic Community), Spain had to adapt its legislation around phytosanitary products to the European one, and since then, the European Commission has overseen the approval of these products. In Spain, all products authorized for use are listed under the National Register of Phytosanitary Products (MAPA 2022). The most used insecticides since the 1990s have been those with *Bacillus thuringiensis* as active ingredient, as well as azadirachtin, alpha-cypermethrin, cypermethrin, deltamethrin, diflubenzuron or etopenfrox. For instance, in Catalonia (northestern Spain), where pine forests are facing mounting pressure by *Thaumetopoea pityocampa* due to increasingly milder winters, ~20,000 ha/year have been treated with *B. thuringiensis* over the last years. Regarding fungicides, copper (cuprocalcic sulfate) and fosetyl-al have been used. Benomyl, which was used to treat cork chancre, was withdrew by the EU in 2003. New products have been tested since then, with methyl thiophanate 50 %[SC]P/V showing the most promising results in preventing the appearance of the fungus and being currently used as an exception (its use has not been authorized for forestry yet, only for agriculture). Treatments with *B. thuringensis* are being tested as an alternative to the fungicide methyl thiophanate, but because the concentration of the active ingredient needed is so low, companies tend to find the process of authorizing these agricultural products for forestry purposes unworthy. Currently, parasitoids are being studied as a biological control method against pest species, which is a more targeted method and aims to balance the population of the pest insect within the ecosystem.

Herbicides are seldom used in forest management in Spain due to the high cost/benefit ratio in most areas characterized by a low profitability of timber harvesting. Furthermore, herbicide treatments are usually not subsidized by public administrations, which further discourages their use in forestry. Thus, the use of herbicides is limited to plantations of fast-growing species (e.g., *Eucalyptus* spp., *Populus* spp., *Pseudotsuga menziesii* and *Pinus radiata*) mainly in northern Spain, with glyphosate being the most used one (Coll et al. 2009).

3.8. Integration of nature protection

Until the 1960s, Spain was a rural country that depended on subsistence farming, and the way nature conservation was understood differed from our current understanding. Soil erosion was one of the main problems the country was facing in relation to deforestation. Hence, nature protection focused on hydrological forest restoration and erosion control. Protection forests ("monte protector") were included in the Forest Law since the beginning of the 20th century to acknowledge the ecological role and importance of those forest areas. Forest harvesting and grazing were more restricted in these forests than in other areas without such protection status. The 1957 Forest Law regulated several issues concerning national parks and represented a shift in the way nature protection was addressed in the legislation. In addition to historical and aesthetic criteria, ecological criteria were considered in the design of the national park network and in the declaration of new protected areas.

During the 1970s – 1990s, the heightened environmental awareness resulted in an increase in the forest area under nature protection status. In 1975, the Law on Natural Protected Areas was approved, which included new types of protected areas beyond the category of national park. Several national parks representing different forest ecosystems (including the laursilva forest in the Canary Islands) were reclassified and their areas expanded.

Since the 1990s, nature protection has taken a predominant role in the way forests are managed, which has been reflected in several policies and strategies targeting issues such as biodiversity conservation and wildfire prevention. The integration of nature protection has been realized through different instruments including the expansion of the network of protected areas (mainly through the implementation of the European Natura 2000 network) and the development of forest certification systems. Currently, over 40 % of Spanish forests are protected (11,187 thousand hectares of which 7,400 thousand are woodlands), in which forest management may be limited/restricted depending on the protection status. Regarding sustainable forest management certification, there are currently 2,300,000 ha of forest certified through PEFC and 335,000 ha through FSC (12.5 % and 1.8 % of the forested area, respectively) (MITECO 2020). Diverse conservation practices have been implemented in forest management over the last years, and include:

- Protecting key habitats and structures required by endangered species, such as certain shrubs that produce food (e.g., wild berries) for brown bear and capercaillie, or deadwood for woodpeckers and owls.
- Managing entire forest systems protected by European directives (e.g., forests dominated by *Pinus nigra* subsp. *salzmanii* and *Quercus pyrenaica*) to ensure they prevail over time and adapt to climate change.
- Reducing wildfire risk by managing fuel load in the increasingly abandoned forest ecosystems of the Mediterranean area and creating stand and forest structures with "fuel" discontinuities to slow down fire propagation (mostly based on public subsidies).

- The inclusion of biodiversity indicators in the most recent National Forest Inventory to monitor the development of biodiversity over time (Asensio et al. 2005).
- Strategies to control or even eradicate certain invasive plant species (e.g., *Ailanthus altissima*).

3.9. Cutting regime

Although cutting regimes have not changed much in Spain since the 1940s, some differences can be pointed out. Timber harvesting tended to be more intense between 1940 and 1970 due to the autarchy established under Francos dictatorship. For instance, *Quercus* coppice stands were intensively managed for charcoal production during this period. During the next period (1970–1990), forest management practices started to be gradually abandoned in many natural forests (namely in the Mediterranean region), whereas short rotation plantations were pervasive in northern Spain.

During the last decades (1990s – present), the abandonment of forest management practices in Mediterranean natural forests has continued due to the low economic profitability of timber harvesting, but the emergence of whole tree harvesting for biomass has led to some of these forests being managed again. The low intensity of forest management is illustrated by the fact that the current harvesting intensity (i.e., the ratio between harvested timber and annual forest growth) in northeastern Spain is ∼ 25 %, whereas the average intensity within Europe is ∼ 60 %. Similarly, and although the area with forest management plans has progressively increased over time (Fig. 3), only ∼ 20 % of the forests in Spain have a management plan. Yet, the existence of a forest management plan does not imply active management, especially in the absence of subsidies.

Cutting regimes vary depending on the climatic region and type of forest. In northern Spain, planted stands of even-aged, fast-growing species are usually intensively managed for wood or biomass and clearcut or coppiced (in the case of re-sprouting species such as eucalypts and poplars) following short rotations. Coppice or coppice with standards is often used with *Quercus* species, which allows for uneven-aged management. Note that *Quercus suber* forests in Spain are not managed for timber but for cork production. Other broadleaved species, such as *Fagus sylvatica*, can also be managed either as even-aged or uneven-aged systems. In some areas dominated by native pines with clear timber production purposes and acceptable economic profitability (e.g., natural forests in central Spain), stands are managed following even-aged forestry with shelterwood methods. However, in some other areas (e.g., northeastern Spain), pine forests have been and still are managed using continuous cover forestry aiming at harvesting those dominant trees of higher economic value.

3.10. Tree maturity

Forest management practices in terms of tree maturity did not change much between 1940 and 1990. In *Quercus* systems (traditionally/often managed as coppice stands), the coppice felling age was low (15–20 years in good sites, 25–30 years in medium-quality sites) compared to the lifespan of the stump, which can range from 200–300 (e.g., *Q. faginea*) to 700–800 (e.g., *Q. ilex*) years (Serrada et al. 2008). Management patterns in tree maturity were similar for chestnut stands (*Castanea sativa*). On the other hand, it may be also considered that, in natural stands, the felling age and potential lifespan of these species/systems are similar since the stumps tend to remain until they are too old. For native pine species such as *Pinus nigra* and *P. sylvestris*, the difference between felling age (80–120 years) and potential lifespan (150–600 years) is usually lower than for *Quercus* species. In the case of fast-growing species in plantations, the management of which is characterized by short rotations (i.e., young felling age), the difference between felling age and potential lifespan tends to be large: 12–18 years *vs* < 100 years for poplars, 10–15 years *vs* 100–150 years for eucalypts, and 30–50 years *vs* 200 years for *Pinus radiata*.

The main change in tree maturity since the 1990s has been the recent development of short-rotation coppice which is mainly intended to produce biomass for bioenergy. The rotation time tends to range between 2 and 10 years, which is considerably shorter than the lifespans of the species used (e.g., eucalypts, poplars). In natural stands, it is now common practice to leave 5–10 trees per hectare over the felling age as well as dead wood for biodiversity protection.

3.11. Wood removals

Forest harvesting during the 1940–1970 period followed the tree-length or shortwood approach depending on the dimensional characteristics required by the industry for different timber products. The residues that were not used after cutting (branches, crown and foliage) were not removed from the forest but remained scattered over the harvested area or were piled and burned afterwards. At the beginning of this period, these residues (especially the thickest branches) were often collected by locals as fuelwood to be used in their households. In the case of forest systems with re-sprouting species (e.g., eucalypts and poplars) that were not managed as coppice stands, the stumps were dug out and often burned right after harvesting. Bark was also a common "residue" in

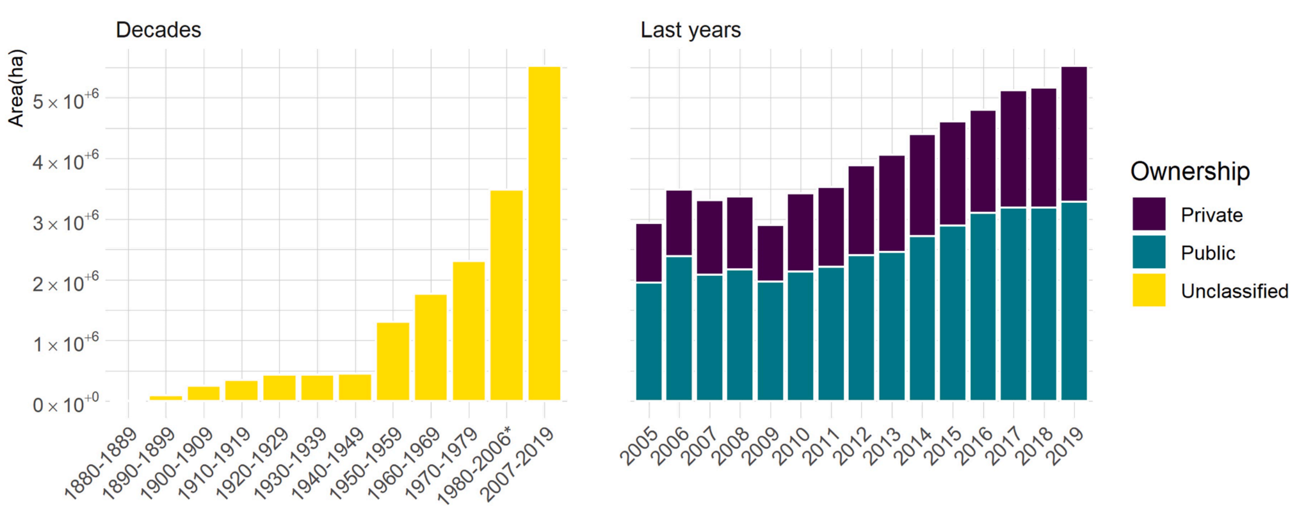

Fig. 3. Historical trends of forest area with forest management plans between 1880 and 2019 (decades, left panel) and between 2005 and 2019 (yearly values, right panel). The asterisk (*) indicates approximate values. (Sources: SECF 2010, MITECO 2021).

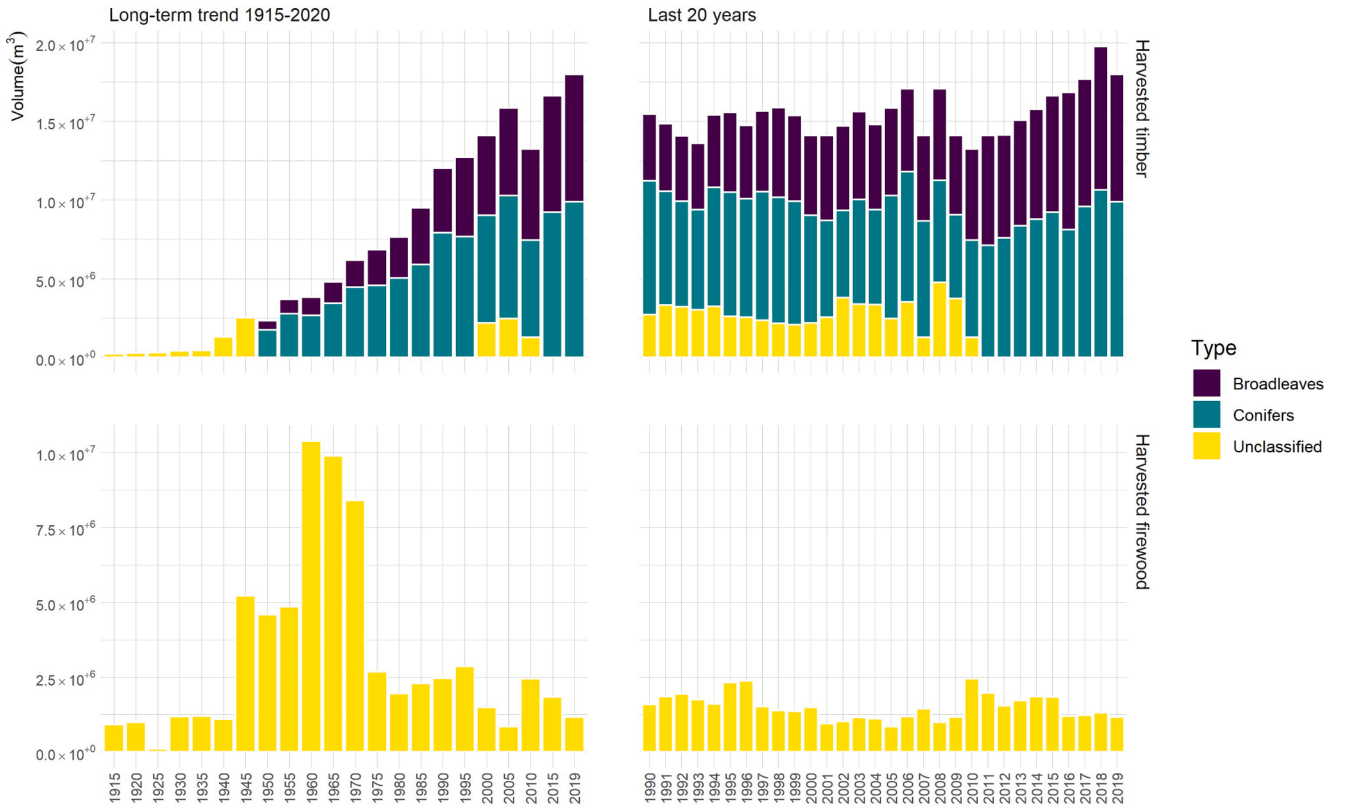

Fig. 4. Historical (1915–2019, left) and recent (1990–2019, right) trends in harvested timber (top) and firewood (bottom) volumes in Spain. (Source: INE 2021).

pine forests that was very often left in the forest after post-harvest manual debarking operations.

From the 1970s onwards, forest harvesting also followed the tree-length or shortwood systems, meaning that branches, crowns and foliage were left on the forest ground after harvesting operations. These side products were not usually processed, although sometimes they were shredded with hammer-cutters and chippers, and exceptionally, piled and burned. During the last period, attempts were made to use the stumps for bioenergy production when a change in the main species (from *Eucalyptus* spp. to *Quercus* spp.) or in a clone (in poplar plantations) was sought after. These stumps were extracted and ground *in situ* using stump grinders. The increasing demand for forest biomass in the last decade is promoting the full tree harvesting system in some conifer stands, in which the entire tree (including branches and crowns) is being chipped and used. This harvesting system is also being applied in burned forests when the products are not of commercial interest. The volume of timber harvested remained low until the 1940s but increased significantly between 1940 and 1960 due to the international isolation Spain faced during Franco's dictatorship (Fig. 4). The volume of firewood harvested decreased considerably since the 1960s due to the emergence of new sources of energy and has fluctuated considerably since the 1990s. Conversely, the volume of timber harvested has followed an upward trend since the 1960s and has remained fairly stable during the last two decades. Conifers represented 75 % of the timber harvested in the 50s, but that percentage has decreased over time until the current value of 55 % (Fig. 4). The largest volume of harvested conifers corresponds to *Pinus radiata* and *P. pinaster* (38 % and 35 % of the harvested conifers in 2017, respectively), whereas eucalypts make up for most of the volume of harvested broadleaves (86 % in 2017) followed by poplars (7 %) (MITECO 2021).

4. Discussion

In this study we reviewed the development since the mid-20th century of several key features of forest management practices in Spain. Understanding how forests have been and are managed is crucial for determining how management could be improved to promote multi-functionality and better face current and future environmental challenges. Thus, information on historical management practices can serve as a basis for defining the contribution that forest management can have to climate change mitigation (e.g., Grassi et al. 2018, Gusti et al. 2020). Our study also provides insights into management decisions other than species choice, cutting regime, maturity and wood removals, which are the ones typically used for such assessments.

Several decisions show a development towards increased multi-functionality and sustainability of forest management practices in Spain (Table 3). The integration of nature protection in this country has evolved from a segregative approach through the creation of national parks (i.e., protection islands) during the first period (1940–1970) to an integrative approach by the implementation of conservation within forestry practices (from planning to execution), a development that agrees with trends seen elsewhere (Boncina 2011, Van der Maaten-Theunissen & Schuck 2013). The adoption of certification schemes is believed to have strengthened the sustainability of forestry practices and has increased over the last 15 years (MITECO 2021). However, the adoption of these schemes in Spain is a) low (13.4 %) compared to the European average (>50 %) (Forest Europe 2020), b) often motivated by market factors (e.g., attracting customer attention, the improvement of companies' corporate image) (Zubizarreta et al. 2021), and c) certified plantations are not necessarily perceived by stakeholders as the most sustainable ones (Díaz-Balteiro & García de Jalón 2017). Similarly, there has been an increase over the years in the forested area with sustainable forest management plans, but the proportion of forests with management plans is still low compared to the European average (20 % and 70 % in 2017, respectively, Bravo et al. 2017). There has also been a change towards more sustainable decisions in terms of soil preparation, which has evolved from continuous methods in which most of the area to be reforested is disturbed, to spot methods which disturb a more limited

Table 3
Semi-quantitative assessment of the intensity of intervention (1 – 5 scale: least – most intensive) of several forest management decisions (rows) during each of the three study periods (columns). The degree of intensity has been determined following the categories defined by Duncker et al. (2012a) (i.e., "*The intensity of manipulation associated with a particular forest management approach results from the deliberate alteration of key stand variables through the use of production factors*").

	Decision	1945–1970					1970–1990					1990-now					Average
		Least intensive			Most intensive		Least intensive			Most intensive		Least intensive			Most intensive		
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	
1	Naturalness of tree species composition				X				X					X			3.3
2	Tree improvement		X						X					X			2.7
3	Type of regeneration			X					X						X		3.3
4	Machine operation		X						X						X		3.0
5	Soil cultivation				X				X					X			3.3
6	Fertilization / Liming	X						X						X			2.0
7	Application of chemical agents				X				X				X				3.0
8	Integration of nature protection				X				X				X				3.0
9.1	Wood removals (stem)			X					X					X			3.0
9.2	Wood removals (residues)	X						X					X				1.7
9.3	Wood removals (stumps)	X					X						X				1.3
10	Final harvest system			X					X					X			3.0
11	Maturity			X					X					X			3.0
AVERAGE SCORE		**2.69**					**2.69**					**2.85**					**2.74**

and targeted area (i.e., the area around the planting hole). Such a development in site preparation, which has been possible in part due to improvements in FRMs and machinery, is believed to minimize environmental impacts while improving seedling performance (Löf et al. 2012). One of the major risks related to forests in southern Europe, especially in low-productivity Mediterranean forests that are expanding and becoming increasingly dense due to rural abandonment, is that of forest fires (Seijo 2005, San-Miguel-Ayanz & Camia 2010). As such, fire prevention is becoming an increasingly important function of forest management and an key issue of territorial development and planning in Spain, which is critical considering that the risk of wildfires is predicted to increase, especially in the Mediterranean Basin (Bowman et al. 2017).

The naturalness of tree species is a complex and controversial decision in forest management (e.g., Brockerhoff et al. 2008, Pötzelsberger et al. 2020). The growing demand for timber and biomass as well as a potentially greater capacity of non-native trees to adapt to climate change has resulted in a growing interest in these species in Europe (Krumm and Vitkova 2016). However, the environmental concerns around non-native species have led to multiple social conflicts among scientists, stakeholders and the general public (Veiras and Soto 2011, Dickie et al. 2014). Native tree species dominate Spanish forests, which is a result of forest management having mostly relied on native trees for large-scale reforestations (pines during the first period and oak trees from 1990 onwards) and the capacity of native species to colonize abandoned agricultural lands (Vadell et al. 2016). However, exotic species have also been used since the mid-19th century. In fact, the forest area covered by non-native species in Spain is higher than the European average (Forest Europe 2020), and the current engagement of Spain in non-native trees in forestry is one of the strongest in Europe (Pötzelsberger et al. 2020). The engagement in exotic species has been especially strong in northern Spain, where *Eucalyptus* and *Pinus radiata* plantations are widespread. The introduction of these two species has been linked to an increased depletion of soil water and nutrients, to changes in biological communities and soil properties, and to an increased fire risk (Williams and Wardle 2007, Soumare et al. 2016, Deus et al. 2018, Calviño-Cancela et al. 2016). Environmental effects of these non-native plantations have also been observed in freshwater ecosystems. For example, altered stream hydrology (e.g., reduced water flow, greater spates during rain events, more severe droughts in the dry season) and functioning (reduced litter decomposition) have been reported in eucalypt plantations (Scott and Lesch 1997, Lara et al. 2009, Cordero-Rivera et al. 2017, Ferreira et al. 2019). Therefore, if forestry in Spain wants to promote sustainability and multifunctionality, the decision around the role that exotic species play in Spanish forests will have to be carefully considered.

Results also showed an increase in the promotion of mixed forests as well as in the share of plantations over the study period. Considering that mixed-species approaches to forestry provide a broader range of ecosystem services relative to monocultures (e.g., Gamfeldt et al. 2013, Felton et al. 2016, Brockerhoff et al. 2017, Liu et al. 2018, Messier et al. 2021), increasing the cover of mixed forests is considered an advancement towards multifunctionality and agrees with the trend observed across Europe (Forest Europe 2020). Spain hosts one of the highest tree diversities in Europe (Ollero & de Dios 2011, Morales Valverde et al. 2011), with almost half of the forest area containing four or more tree species (Forest Europe 2020). One of the positive outcomes provided by mixed-species compared to monospecific forests is a reduced risk of disturbances such as pathogens and pests (Felton et al. 2016, Jactel et al. 2009, 2017). This benefit is especially relevant these days in Spain due to the devastating outbreak of needle blight experienced by *Pinus radiata* monocultures in the Atlantic region of the country between 2018 and 2020 (Mesanza et al. 2021). However, the increase in the share of even-aged plantations (from 8.2 % to 10 %) during the past decades may not be in line with increased multifunctionality, since uneven-aged forestry provides more ecosystem services than even-aged rotation forest management (Pukkala 2016).

Unlike the above-described decisions, which have evolved since the mid-20th century (e.g., soil cultivation, integration of nature protection, naturalness of tree species), other decisions have not changed much (Table 3). That is the case for regeneration method, cutting regime and tree maturity. Semi-natural stands of native conifers were and are naturally regenerated, and even-aged forestry with shelterwood (central Spain) or continuous cover forestry (northeastern Spain) is used to cut the trees at a mature stage (80–120 years old). On the other hand, in the even-aged plantations of fast-growing trees (namely, poplars, eucalypts and *Pinus radiata*) that abound in the northern region, seedlings are planted and clearcut or intensive coppice is used to cut the trees at a fairly young age relative to their potential lifespan. The former approach (continuous cover forestry) is recognized to provide a wider suite of ecosystem services besides timber production in comparison to the latter (conventional rotational forestry), and it is receiving increasingly more attention globally due to concerns about the ecological consequences of intensive forestry practices and a willingness to promote a wider set of management objectives (Duncker et al. 2012b, Sing et al. 2017). However, the wider adoption of alternative silvicultural practices is hindered by several constraints (economic, logistical, informational, cultural, historical) that could be overcome with interventions such as regulations and incentives (Puettmann et al. 2015).

A third forestry approach that has been followed in Spain is that of coppicing *Quercus* stands. Oaks were coppiced quite intensively following 20–30-year rotation cycles up until the 70s, but then this forest management practice started to be gradually abandoned, namely in the Mediterranean region. The consequences of such abandonment are the increasing problems of decay of stands with excessively aged stumps, generalized crown dieback/defoliation, no regeneration from seeds and high flammability. One of the main effects of climate change in the Mediterranean area will be increased aridity (Jansen 2007), which will decrease forest productivity and increase tree mortality (Barbeta et al. 2013, Ogaya et al. 2003). These ecosystems face difficulties in sexual regeneration (Plieninger et al. 2010), especially the agrosystems of *Quercus suber* and *Quercus ilex* "dehesas" (Pulido et al. 2001, Plieninger et al. 2004), and as their lifespan can be of several hundreds of years old (Fernandez et al. 2004), they may not have enough genetic diversity to adapt to future conditions (Soto et al. 2007).

In addition to those three forestry approaches, two of which have remained fairly constant over the study period, a fourth approach has developed recently: short rotation coppice for bioenergy. Following the increased demand for this source of energy worldwide (IEA 2018), more stands of re-sprouting eucalypts and poplars are managed following shorter rotation (2–10 years) practices in Spain. This has allowed for some abandoned Mediterranean forests where the wood was not of sufficient quality for the timber industry to be managed again. In terms of multifunctionality, this type of forestry contributes to guaranteeing energy security as well as to mitigating climate change (Rockstrom et al. 2017, Obersteiner et al. 2018), but it is not free from environmental concerns such as a lower biodiversity compared to natural forests (Vanbeveren and Ceulemans 2019). Additionally, some studies have shown that carbon benefits can be superior when forests are left to regenerate as opposed to converted into short rotation coppice systems (Griscom et al. 2017, Kalt et al. 2019). Yet, because the Mediterranean region is prone to forest fires, such disturbances could cancel out the carbon accumulated in forests for years (Hurteau and Brooks 2011). It is also important to keep in mind that carbon storage is an expensive process in terms of water requirements within the water-limited context of many Mediterranean forest ecosystems. For Mediterranean trees, fixing a gram of carbon may require 1–1.5 kg of water (Sabaté and Gracia 2011). Considering that Spain is one of the most water-limited countries in Europe, and that water resources are already and will increasingly be subject to multiple pressures and stressors (EEA 2021), the role of Mediterranean forests in climate change mitigation and the trade-offs between carbon fixation and water use need to be carefully pondered. Thus, the future development of these forest management decisions (tree maturity, cutting regime, type of regeneration) in Spain will depend on which ecosystem services (e.g., energy provision, climate change mitigation, water regulation, fire prevention, biodiversity) are prioritized, as well as on which strategy is adopted to mitigate and adapt to climate change (Duncker et al. 2012b, Verkerk et al. 2020), especially considering that the degree of multifunctionality of Mediterranean forests may be inherently limited and that trade-offs between ecosystem services are unavoidable (Morán-Ordóñez et al. 2020).

Another forest management decision that has evolved towards intensification is that of fertilization (Table 3). The use of fertilizers in plantations of fast-growing species started in the 1970s and consolidated in the 1990s, partly due to public subsidization that alleviated the high cost of application. Since 2000, there was a change in fertilizer composition based on the trials conducted during the previous decade and prescriptions were refined accordingly. For example, the fertilization of *Pinus radiata* with superphosphates has been recommended to offset the lack of P and excess of N in the soils of northern Spain (Sánchez-Rodrıguez et al. 2002, Zas 2003). The fertilization of eucalypt plantations is also recommended, especially in short-rotation coppice systems, based on studies that have reported a positive effect on wood production (Viera et al. 2016). Regarding poplars, the general rule of thumb is that soils should not be fertilized if the NPK content is of 50, 30 and 100 ppm, respectively (Domínguez 1997). However, it remains unclear whether fertilizing is a good investment (especially in plantations with longer rotations), as there are no conclusive studies on whether the potential revenues from increased timber production compensate for the fertilization costs (which may represent an extra cost of 300 to 500 euros per hectare). This is especially true when considering the orography, climate and soil types in Spain, which hinder application and limit economic profitability.

Unlike the use of fertilizers, the application of chemical agents has diminished in intensity during the study period. This decrease has followed, in part, several bans around some of the most harmful products to humans and the environment. Instead, biological control treatments started to be applied in the 1990s, with microbial insecticides based on *Bacillus thuringiensis* being widely used during the past two decades. The development of equipment enabling ultra-low volume treatments has also contributed to a less intensive application of chemical agents. Because climate change presents an uncertain future in terms of pathogen and insect outbreaks (Dale et al. 2001), control treatments may have to evolve quickly in the future to tackle new pests/diseases or the altered behaviour and physiology of species already present within a system. Additionally, forest management decisions that contribute to preventing and mitigating the negative impacts of such outbreaks should be adopted. This includes the promotion of genetic diversity in FRMs to boost resilience or forestry practices that enhance protection against outbreaks such as establishing more diverse mixed-species, uneven-aged forests (Pautasso et al. 2010, Felton et al. 2016, Jactel et al. 2017).

Finally, other management decisions have developed considerably since 1940 but need to advance further if the management of Spanish forests is going to successfully meet the challenges ahead. For instance, the use of machinery in forest management has intensified (Table 3). This mechanization was delayed in Spain compared to other countries, but the lack of workforce in the forestry sector during the 1980s-1990s propelled it. However, except for some prototypes designed in Spain between 1970 and 1990, the mechanization of forestry operations has mostly been carried out with machinery designed in and imported from Central European countries. Because the orographic and forest conditions in Spain differ from those in Central Europe, these machines are not necessarily well suited for the former, and their use has led to some controversy (Edeso et al. 1999, Ampoorter et al. 2012, Casamitjana et al. 2012). Furthermore, the data on machinery used for forestry and agriculture tends to be aggregated, and there is a lack of records on the machinery (type, age…) used for silvicultural practices (Calvo et al. 2005). Therefore, there is the need for research and innovation on machinery adapted to the conditions in Spain (e.g., natural or semi-natural hardwood forests), as well as for a reliable inventory of the machinery being used in the forestry industry.

The development and use of FRMs has also developed during the study period, but further efforts are required to ensure that FRMs are suitable for present/future conditions and sufficiently genetically diverse to face a changing environment. The history of genetic improvement in Spain is like that of other European countries: the efforts have been focused on species of greater economic interest neglecting native species until recent times (Ennos et al. 1998). In the case of Spain, efforts have focused on *Eucalyptus*. sp, *Populus*. sp, *Pinus pinaster* and *P. radiata*. Currently, there are 0.9 FRM sources per 1000 km^2 in Spain, which is a low number when compared to countries like Czechia (61.0) or Germany (26.4) (Pötzelsberger et al. 2020). The current crisis of climate change, the unprecedented biodiversity loss and changes in forest policies have prompted efforts to preserve and enhance the genetic diversity of native tree species in the last period (González-Martínez & Martin-Albertos 2000, Fernández et al. 2000), and the growing number of restoration initiatives has led to a growing interest in and demand for species with local genotypes (Thomas et al. 2014, Di Sacco et al. 2021). In a situation in which environmental changes are faster than trees can adapt genetically (Kremer et al. 2012), reforestation with genetically diverse FRMs will be one of the tools facilitating climate change adaptation (Rajora & Mosseler 2001, Kolström et al. 2011, Vinceti et al. 2020).

5. Conclusions

Our study shows that different forest management decisions in Spain have evolved differently, with some showing a gradual shift towards multifunctionality, others moving towards a more intensive type of forestry, and others not changing much since the 1940s. The analysis has also showed clear regional differences, with forests in the Atlantic region being managed in a more production-centered way as opposed to the more protection-centered way in the Mediterranean region. The description and discussion of the trends allow to anticipate where the Spanish forest management is headed as well as what management decisions should be reconsidered according to the objectives of the country's forest policy. If the Spanish forestry policy is committed to improving and activating forest management, it is important to consider the multifunctional role of forests and all the benefits they provide (e.g., timber and non-timber products, water regulation, biodiversity conservation, fire prevention, carbon sequestration, recreational opportunities). As such, several decisions regarding the cutting regime, tree maturity and/or the naturalness of tree species may have to be reconsidered if the country wants to transition from conventional timber-centered rotational forestry to alternative silvicultural approaches that promote multifunctionality (e.g., continuous cover forestry). Such a transition towards mixed-species, uneven-aged forests would also facilitate rising to one of the main challenges that Spanish forest management faces: to develop a climate-smart forestry that contributes to the mitigation of and adaptation to global change. In the same vein, genetic improvement needs to focus not only on the most productive tree species, but also on those species that are able to adapt to the increasingly arid conditions in the Mediterranean region. Current decisions on the naturalness of species composition may also need to be revisited, and species or provenances that can better thrive under future climatic conditions may have to be considered. Machine operation should also be tailored to the conditions of Mediterranean forestry and topography, either by adapting existing machines or by developing new ones. Further research on the development of forest management practices in other European countries is needed to compare trends and, thus, draw valuable lessons for European forest policy decision making.

CRediT authorship contribution statement

Enric Vadell: Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Jesús Pemán:** Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Supervision. **Pieter Johannes Verkerk:** Conceptualization, Methodology, Writing – review & editing, Project administration. **Maitane Erdozain:** Formal analysis, Data curation, Writing – review & editing. **Sergio de-Miguel:** Conceptualization, Investigation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

SdM benfitted from a Serra-Húnter Fellowship provided by the Government of Catalonia. PJV contributed to this research as part of the GenTree project, which has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 676876. ME and SdM also contributed to this research as part of the SUPERB project, which has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 101036849. The authors also wish to thank for all the relevant information based on expert knowledge provided by forestry experts Roque Rodríguez Soalleiro and Aitor Onaindia along the data gathering process.

References

Albaladejo, C.M., Gómez, A.N., Santiago, A.V.C., 2016. El Instituto Español de Entomología (CSIC) y la multitud molesta. Asclepio 68 (1), 125.
Alberdi, I., Saura, S., Martínez, F.J., 2005. El estudio de la biodiversidad en el tercer Inventario Forestal Nacional. Cuadernos de la Sociedad Española de Ciencias Forestales 19, 11–19.
Alia, R., Gil, L., Pardos, J.A., Catalan, G., 1991. Interacción procedencia-edad en 52 procedencias de Pinus pinaster Ait. en España. Forest Syst. 1, 11–24.
Álvarez-González, J.G., Cañellas, I., Alberdi, I., Gadow, K.V., Ruiz-González, A.D., 2014. National forest inventory and forest observational studies in Spain: Applications to forest modeling. For. Ecol. Manage. 316, 54–64.
Ampoorter, E., De Schrijver, A., Van Nevel, L., Hermy, M., Verheyen, K., 2012. Impact of mechanized harvesting on compaction of sandy and clayey forest soils: results of a meta-analysis. Ann. Forest Sci. 69 (5), 533–542.
Antón, M.T., 2011. Las actuaciones forestales como vector de transformación de los paisajes de la Cordillera Cantábrica de León: evolución histórica y perspectivas de futuro. In: *La evolución del paisaje vegetal y el uso del fuego en la Cordillera Cantábrica*. Fundación Patrimonio Natural de Castilla y León, pp. 345–363.
Armenteras, A.A., 1903. Árboles y Montes. Curiosidades artísticas e históricas, Imprenta Ricardo Rojas, Madrid.
Arregui, R.Z., Merlo, E., 2008. El programa de mejora genética de *Pinus pinaster* en Galicia. Boletín Informativo CIDEU 6, 5–24.
Arregui, A., Sierra, R., Espinel, S., Aragones, A., 1999. Estimación de parámetros genéticos en un ensayo de progenie de *Pinus radiata* D. Don en el país vasco. Forest Syst. 8 (1), 119–128.
Artigas, P., 1890. Selvicultura o cria y cultivo de los montes. Imprenta de Moreno y Rojas, Madrid.
Asensio, I.A., de Toda, S.S.M., Millán, F.M., 2005. El estudio de la biodiversidad en el Tercer Inventario Forestal Nacional. Cuadernos de la Sociedad Española de Ciencias Forestales 19, 11–19.
Barbeta, A., Ogaya, R., Peñuelas, J., 2013. Dampening effects of long-term experimental drought on growth and mortality rates of a Holm oak forest. Glob. Change Biol. 19 (10), 3133–3144.
Blanco, E., Casado, M.A., Costa, M., Escribano, R., García, M., Génova, M., Regato, P., 1997. Los bosques ibéricos. Una interpretación geobotánica, Planeta, Barcelona.
Bocio, I., Navarro, F.B., Ripoll, M.A., Jiménez, M.N., De Simón, E., 2004. Holm oak (*Quercus rotundifolia* Lam.) and Aleppo pine (*Pinus halepensis* Mill.) response to different soil preparation techniques applied to forestation in abandoned farmland. Ann. Forest Sci. 61 (2), 171–178.
Boncina, A., 2011. Conceptual approaches to integrate nature conservation into forest management: a Central European perspective. Int. Forest. Rev. 13, 13–22.
Borrass, L., Kleinschmit, D., Winkel, G., 2017. The "German model" of integrative multifunctional forest management—Analysing the emergence and political evolution of a forest management concept. Forest Policy Econ. 77, 16–23.
Bowman, D.M.J.S., Williamson, G.J., Abatzoglou, J.T., Kolden, C.A., Cochrane, M.A., Smith, A.M., 2017. Human exposure and sensitivity to globally extreme wildfire events. Nature Ecol. Evolut. 1, 0058.
Bravo, F., Guijarro, M., Cámara, A., Díaz Balteiro, L., Fernández, P., Pemán, J., Ruiz Peinado, R., 2017. La situación de los bosques y el sector forestal en España – ISFE. Available at: http://secforestales.org/sites/default/files/archivos/isfe2017_final_julio2017.pdf [accessed May 2022].
Brockerhoff, E.G., Jactel, H., Parrotta, J., Quine, C.P., Sayer, J., 2008. Plantation forests and biodiversity: oxymoron or opportunity? Biodivers. Conserv. 17, 925–951.
Brockerhoff, E.G., Barbaro, L., Castagneyrol, B., Forrester, D.I., Gardiner, B., González-Olabarria, J.R., Lyver, P.O.B., Meurisse, N., Oxbrough, A., Taki, H., Thompson, I.D., van der Plas, F., Jactel, H., 2017. Forest biodiversity, ecosystem functioning and the provision of ecosystem services. Biodivers. Conserv. 26 (13), 3005–3035.
Calviño-Cancela, M., Chas-Amil, M.L., García-Martínez, E.D., Touza, J., 2016. Wildfire risk associated with different vegetation types within and outside wildland-urban interfaces. For. Ecol. Manag. 372, 1–9.
Calvo, A.X., Herruzo, C., Balteiro, L.D., Martínez, M., 2005. Caracterización de la concentración industrial y de la localización en la industria forestal española. In: *IV Congresos Forestales:* 04. Available at: http://secforestales.org/publicaciones/index.php/congresos_forestales/article/view/16573 [accessed August 2022].
Casamitjana, M., Loaiza, J.C., Simon, N., Frigola, P., 2012. Ecological aspects and effects of forestry management on a population of Hermann's tortoise (*Testudo hermanni hermanni*) in Catalonia (Spain). Basic Appl. Herpetol. 26, 73–86.
Castell, C., Castelló, J.I., 1996. Metodología y resultados de la siembra aérea efectuada en el Parque Natural del Garraf. Montes 46, 51–57.

Cervera, T., Garrabou, R., Tello, E., 2015. Política forestal y evolución de los bosques en Cataluña desde el siglo xix hasta la actualidad. Investigaciones de Historia Económica-Econ. History Res. 11 (2), 116–127.
Coll, L., Navarro Cerrillo, R.M., Vericat, P., 2009. Spain. In: Willoughby, I., Balandier, P., Bentsen, N.S., McCarthy, N., Claridge, J. (Eds.), Forest Vegetation Management in Europe: Current Practice and Future Requirements. COST Office, Brussels.
Cordero-Rivera, A., Álvarez, A.M., Álvarez, M., 2017. Eucalypt plantations reduce the diversity of macroinvertebrates in small forested streams. Anim. Biodivers. Conserv. 40, 87–97.
Dale, V.H., Joyce, L.A., McNulty, S., Neilson, R.P., Ayres, M.P., Flannigan, M.D., Hanson, P.J., Irland, L.C., Lugo, A.E., Peterson, C.J., Simberloff, D., Swanson, F.J., Stocks, B.J., Wotton, B.M., 2001. Climate change and forest disturbances. Bioscience 51 (9), 723–734.
Deus, E., Silva, J.S., Castro-Díez, P., Lomba, A., Ortiz, M.L., Vicente, J., 2018. Current and future conflicts between eucalypt plantations and high biodiversity areas in the Iberian Peninsula. J. Nat. Conserv. 45, 107–117.
Di Sacco, A., Hardwick, K.A., Blakesley, D., Brancalion, P.H.S., Breman, E., Cecilio Rebola, L., Chomba, S., Dixon, K., Elliott, S., Ruyonga, G., Shaw, K., Smith, P., Smith, R.J., Antonelli, A., 2021. Ten golden rules for reforestation to optimize carbon sequestration, biodiversity recovery and livelihood benefits. Glob. Change Biol. 27 (7), 1328–1348.
Díaz-Balteiro, L., García de Jalón, S., 2017. Certifying forests to achieve sustainability in industrial plantations: opinions of stakeholders in Spain. Forests 8 (12), 502.
Dickie, I.A., Bennett, B.M., Burrows, L.E., Nuñez, M.A., Peltzer, D.A., Porté, A., Richardson, D.M., Rejmánek, M., Rundel, P.W., van Wilgen, B.W., 2014. Conflicting values: ecosystem services and invasive tree management. Biol. Invasions 16 (3), 705–719.
Domínguez, A., 1997. Plantaciones Forestales. Tratado de Fertilización. Ediciones Mundi-Prensa, En, pp. 518–522.
Duncker, P.S., Barreiro, S.M., Hengeveld, G.M., Lind, T., Mason, W.L., Ambrozy, S., Spiecker, H., 2012a. Classification of Forest Management Approaches: A New Conceptual Framework and Its Applicability to European Forestry. Ecol. Soc. 17 (4).
Duncker, P.S., Raulund-Rasmussen, K., Gundersen, P., Katzensteiner, K., De Jong, J., Ravn, H.P., Smith, M., Eckmüllner, O., Spiecker, H., 2012b. How forest management affects ecosystem services, including timber production and economic return: synergies and trade-offs. Ecol. Soc. 17 (4), 50.
EC, 2013. A new EU forest Strategy: for forests and the forest-based sector. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions.
Edeso, J.M., Merino, A., Gonzalez, M.J., Marauri, P., 1999. Soil erosion under different harvesting managements in steep forestlands from northern Spain. Land Degrad. Dev. 10 (1), 79–88.
EEA, 2021. Water resources across Europe — confronting water stress: an updated assessment. European Environment Agency, Copenhagen.
Ennos, R.A., Worrell, R., Malcolm, D.C., 1998. The genetic management of native species in Scotland. Forestry: Int. J. Forest Res. 71 (1), 1–23.
Forest Europe, 2020. State of Europe's Forests 2020. Available at: https://foresteurope.org/state-europes-forests-2020/ [accessed May 2022].
Felipe-Lucia, M.R., Soliveres, S., Penone, C., Manning, P., van der Plas, F., Boch, S., Prati, D., Ammer, C., Schall, P., Gossner, M.M., 2018. Multiple forest attributes underpin the supply of multiple ecosystem services. Nat. Commun. 9, 4839.
Felton, A., Nilsson, U., Sonesson, J., Felton, A.M., Roberge, J.M., Ranius, T., Ahlström, M., Bergh, J., Björkman, C., Boberg, J., Drössler, L., Fahlvik, N., Gong, P., Holmström, E., Keskitalo, E.C.H., Klapwijk, M.J., Laudon, H., Lundmark, T., Niklasson, M., Wallertz, K., 2016. Replacing monocultures with mixed-species stands: Ecosystem service implications of two production forest alternatives in Sweden. Ambio 45 (January), 124–139.
Fernández, L., Díaz, V., Cogolludo, A., Pereira, L., 2000. Forest genetic resource conservation of noble hardwoods in Spain. *Investigación Agraria, Sistemas y Recursos Forestales*, (Fuera de S. 2) 71–91.
Fernandez, J.B., Hierro, R.S., Gómez, S.R., 2004. Brotación en encinas (Quercus ilex subsp. ballota) con edades elevadas. Experiencias en el monte de Riofrío (Segovia). Forest Syst. 13 (4), 127–141.
Ferreira, V., Boyero, L., Calvo, C., Correa, F., Figueroa, R., Gonçalves, J.F., Goyenola, G., Graça, M.A.S., Hepp, L.U., Kariuki, S., López-Rodríguez, A., Mazzeo, N., M'Erimba, C., Monroy, S., Peil, A., Pozo, J., Rezende, R., Teixeira-de-Mello, F., 2019. A global assessment of the effects of eucalyptus plantations on stream ecosystem functioning. Ecosystems 22 (3), 629–642.
Gamfeldt, L., Snäll, T., Bagchi, R., Jonsson, M., Gustafsson, L., Kjellander, P., Ruiz-Jaen, M.C., Fröberg, M., et al., 2013. Higher levels of multiple ecosystem services are found in forests with more tree species. Nat. Commun. 4, 1340.
González-Martínez, S.C., Martin-Albertos, S., 2000. Conservación de recursos genéticos de coníferas en España. Investigación Agraria 9 (2), 151–184.
Grassi, G., Pilli, R., House, J., Federici, S., Kurz, W.A., 2018. Science-based approach for credible accounting of mitigation in managed forests. Carbon Balance Manage. 13, 8.
Griscom, B.W., Adams, J., Ellis, P.W., Houghton, R.A., Lomax, G., Miteva, D.A., Schlesinger, W.H., Shoch, D., Siikamäki, J.V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R.T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M.R., Fargione, J., 2017. Natural climate solutions. PNAS 114 (44), 11645–11650.
Gusti, M., Di Fulvio, F., Biber, P., Korosuo, A., Forsell, N., 2020. The effect of alternative forest management models on the forest harvest and emissions as compared to the forest reference level. Forests 11, 794.
Gutiérrez-Hernández, O., Senciales-González, J.M., García-Fernández, L.V., 2016. Evolución de la superficie forestal en Andalucía (1956-2007). Procesos y factores. *Revista de Estudios Andaluces* 33 (1), 111-148.
Hernández, L., Cañellas, I., Alberdi, I., Torres, I., Montes, F., 2014. Assessing changes in species distribution from sequential large-scale forest inventories. Ann. Forest Sci. 71 (2), 161–171.
Hernández-Morcillo, M., Torralba, M., Baiges, T., Bernasconi, A., Bottaro, G., Brogaard, S., Bussola, F., Díaz-Varela, E., Geneletti, D., Grossmann, C.M., Kister, J., Klingler, M., Loft, L., Lovric, M., Mann, C., Pipart, N., Roces-Díaz, J.V., Sorge, S., Tiebel, M., Plieninger, T., 2022. Scanning the solutions for the sustainable supply of forest ecosystem services in Europe. Sustain. Sci.
Hurteau, M.D., Brooks, M.L., 2011. Short- and long-term effects of fire on carbon in US dry temperate forest systems. Bioscience 61 (2), 139–146.
IEPBN, 2021. Informe sobre el estado del patrimonio natural y de la biodiversidad en España a 2020. MITECO, Madrid. Available at: https://www.miteco.gob.es/es/biodiversidad/temas/inventarios-nacionales/inventario-espanol-patrimonio-natural-biodiv/informe-anual/Informe_2020_IEPNB.aspx [accessed May 2022].
INE, 2021. Anuario estadístico de España. 1858-2011. Instituto Nacional de Estadística. Madrid. https://www.ine.es/prodyser/pubweb/anuarios_mnu.htm.
International Energy Agency (IEA), 2018. Renewables 2018 - analysis and forecasts to 2023. p. 211. France.
Jactel, H., Nicoll, B.C., Branco, M., Gonzalez-Olabarria, J.R., Grodzki, W., Långström, B., Moreira, F., Netherer, S., Orazio, C., Piou, D., Santos, H., Schelhaas, M.J., Tojic, K., Vodde, F., 2009. The influences of forest stand management on biotic and abiotic risks of damage. Ann. Forest Sci. 66, 701.
Jactel, H., Bauhus, J., Boberg, J., Bonal, D., Castagneyrol, B., Gardiner, B., Gonzalez-Olabarria, J.R., Koricheva, J., Meurisse, N., Brockerhoff, E.G., 2017. Tree diversity drives forest stand resistance to natural disturbances. Current Forestry Reports 3, 223–243.
Jansen, E., 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. *Palaeoclimate*. United Kingdom Cambridge University Press, Cambridge, pp. 433–497.
Jepsen, M.R., Kuemmerle, T., Müller, D., Erb, K., Verburg, P.H., et al., 2015. Transitions in European land-management regimes between 1800 and 2010. Land Use Policy 49, 53–64.
Kalt, G., Mayer, A., Theurl, M.C., Lauk, C., Erb, K.H., Haberl, H., 2019. Natural climate solutions versus bioenergy: Can carbon benefits of natural succession compete with bioenergy from short rotation coppice? GCB Bioenergy 11 (11), 1283–1297.
Kolström, M., Lindner, M., Vilén, T., Maroschek, M., Seidl, R., Lexer, M.J., et al., 2011. Reviewing the science and implementation of climate change adaptation measures in European forestry. Forests 2 (4), 961–982.
Kremer, A., Ronce, O., Robledo-Arnuncio, J.J., Guillaume, F., Bohrer, G., Nathan, R., Schueler, S., 2012. Long-distance gene flow and adaptation of forest trees to rapid climate change. Ecol. Lett. 15 (4), 378–392.
Krumm, F., Vitkova, L. (Eds.), 2016. Introduced tree species in European forests: opportunities and challenges. European Forest Institute. 423 p.
Lara, A., Little, C., Urrutia, R., McPhee, J., Álvarez-Garretón, C., Oyarzún, C., Soto, D., Donoso, P., Nahuelhual, L., Pino, M., Arismendi, I., 2009. Assessment of ecosystem services as an opportunity for the conservation and management of native forests in Chile. For. Ecol. Manag. 258, 415–424.
Levers, C., Müller, D., Erb, K., Haberl, H., Jepsen, M.R., Metzger, M.J., Meyfroidt, P., Plieninger, T., Plutzar, C., Stürck, J., Verburg, P.H., Verkerk, P.J., Kuemmerle, T., 2018. Archetypical patterns and trajectories of land systems in Europe. Reg. Environ. Change 18, 715–732.
Liu, C.L.C., Kuchma, O., Krutovsky, K.V., 2018. Mixed-species versus monocultures in plantation forestry: Development, benefits, ecosystem services and perspectives for the future. Global Ecol. Conserv. 15.
Löf, M., Dey, D.C., Navarro, R.M., Jacobs, D.F., 2012. Mechanical site preparation for forest restoration. New Forest. 43 (5–6), 825–848.
Madariaga, J.A., 1909. Repoblación forestal. Medios de dar valor a eriales y terrenos pobres. Imprenta Alemana, Madrid.
MAPA, 2022. Lista comunitaria de sustancias activas aprobadas, excluidas y en evaluación comunitaria, sustancias de bajo riesgo, sustancias candidatas a la sustitución y lista de sustancias básicas. Ministerio de Agricultura, Pesca y Alimentación. Available at: https://www.mapa.gob.es/es/agricultura/temas/sanidad-vegetal/listasustanciasactivasaceptadasexcluidas_tcm30-618972.pdf [accessed August 2022].
Martynova, M., Sultanova, R., Khanov, D., Talipov, E., Sazgutdinova, R., 2020. Forest management based on the principles of multifunctional forest use. J. Sustainable For. 40, 32–46.
Mayer, M., Prescott, C.E., Abaker, W.E.A., Augusto, L., Cécillon, L., Ferreira, G.W.D., James, J., Jandl, R., Katzensteiner, K., Laclau, J.P., Laganière, J., Nouvellon, Y., Paré, D., Stanturf, J.A., Vanguelova, E.I., Vesterdal, L., 2020. Influence of forest management activities on soil organic carbon stocks: A knowledge synthesis. For. Ecol. Manage. 466 (January).
Mendoza, J.G., Olmo, R.M., 1992. Actuaciones forestales públicas desde 1940. Objetivos, criterios y resultados. Agricultura y Sociedad 65, 15–64.
Mendoza, J.G., Olmo, R.M., 2006. Paisajes forestales españoles y sostenibilidad. Tópicos y realidades. Áreas. *Revista Internacional de Ciencias Sociales* 25, 13–29.
Mesanza, N., García-García, D., Raposo, E.R., Raposo, R., Iturbide, M., Pascual, M.T., Barrena, I., Urkola, A., Berano, N., Sáez de Zerain, A., Iturritxa, E., 2021. Weather Variables Associated with Spore Dispersal of *Lecanosticta acicola* Causing Pine Needle Blight in Northern Spain. Plants 10 (12), 2788.
Messier, C., Bauhus, J., Sousa-Silva, R., Auge, H., Baeten, L., Barsoum, N., Bruelheide, H., Caldwell, B., Cavender-Bares, J., Dhiedt, E., Eisenhauer, N., Ganade, G., Gravel, D., Guillemot, J., Hall, J.S., Hector, A., Hérault, B., Jactel, H., Koricheva, J., Zemp, D.C., 2021. For the sake of resilience and multifunctionality, let's diversify planted forests! Conserv. Lett. 15 (1), 1–8.

Millennium Ecosystem Assessment (MEA), 2005. Ecosystems and human well-being: synthesis. Island, Washington, D.C., USA.
MITECO, 2020. Gestión forestal sostenible. Madrid. Available at: https://www.miteco.gob.es/es/biodiversidad/estadisticas/aef2019_06_gfs_tcm30-529159.pdf [accessed August 2022].
MITECO, 2021. Anuarios de estadística forestal. 2005-2019. Madrid. Available at: https://www.miteco.gob.es/es/biodiversidad/estadisticas/forestal_anuarios_todos.aspx [accessed May 2022].
Molina, J.L., Navarro, M., Montero de Burgos, J.L., Herranz, J.L., 1989. Afforestation techniques in Mediterranean countries. ICONA, Madrid.
Morales Valverde, R., Tardío, J., Pardo de Santayana, M., Molina, M., Aceituno-Mata, L., 2011. Biodiversidad y Etnobotánica en España.
Montero, G., 2018. Breve resumen del proceso repoblador en España. In: https://distritoforestal.es/historia-forestal/breve-resumen-del-proceso-repoblador-en-espana. (Accessed 12 September 2022).
Morán-Ordóñez, A., Ameztegui, A., De Cáceres, M., et al., 2020. Future trade-offs and synergies among ecosystem services in Mediterranean forests under global change scenarios. Ecosyst. Serv. 45, 101174.
Navarro Cerrillo, R.M., Serrada Hierro, R., Gómez Mampaso, V., et al., 2021. Siembras y plantaciones. In: Pemán García, J., Navarro Cerrillo, R.M., Prada Sáez, M.A., Serrada Hierro, R. (Eds.), Bases técnicas y ecológicas del Proy. repoblación For. Ministerio para la Transición Ecológica y el Reto Demográfico, Madrid, pp. 722-780.
Navarro-Garnica, M., 1977. Técnicas de forestación. 1975. ICONA, Madrid.
Obersteiner, M., Bednar, J., Wagner, F., Gasser, T., Ciais, P., Forsell, N., et al., 2018. How to spend a dwindling greenhouse gas budget. Nat. Clim. Change 8, 2–12.
Ogaya, R., Peñuelas, J., Martínez-Vilalta, J., Mangirón, M., 2003. Effect of drought on diameter increment of *Quercus ilex*, *Phillyrea latifolia*, and *Arbutus unedo* in a holm oak forest of NE Spain. *Forest Ecol. Manage.*, 180(1-3), 175-184.
Ollero, H.S., de Dios, R.S., 2011. La diversidad de los paisajes españoles. Biodiversidad 109.
Pautasso, M., Dehnen-Schmutz, K., Holdenrieder, O., Pietravalle, S., Salama, N., Jeger, M.J., Lange, E., Hehl-Lange, S., 2010. Plant health and global change - Some implications for landscape management. Biol. Rev. 85 (4), 729–755.
Pemán, J., Arnó, J., 1998. Novedades en mecanización de repoblaciones forestales. Vida Rural 76, 55–58.
Plieninger, T., Pulido, F.J., Schaich, H., 2004. Effects of land-use and landscape structure on holm oak recruitment and regeneration at farm level in *Quercus ilex* L. dehesas. J. Arid Environ. 57 (3), 345–364.
Plieninger, T., Rolo, V., Moreno, G., 2010. Large-scale patterns of *Quercus ilex*, *Quercus suber*, and *Quercus pyrenaica* regeneration in Central-Western Spain. Ecosystems 13 (5), 644–660.
Pötzelsberger, E., Spiecker, H., Neophytou, C., Mohren, F., Gazda, A., Hasenauer, H., 2020. Growing non-native trees in European forests brings benefits and opportunities but also has its risks and limits. Current Forestry Reports 6 (4), 339–353.
Puettmann, K.J., Wilson, S.M.G., Baker, S.C., Donoso, P.J., Drössler, L., Amente, G., Harvey, B.D., Knoke, T., Lu, Y., Nocentini, S., Putz, F.E., Yoshida, T., Bauhus, J., 2015. Silvicultural alternatives to conventional even-aged forest management - What limits global adoption? Forest Ecosyst. 2 (8).
Pukkala, T., 2016. Which type of forest management provides most ecosystem services? Forest Ecosyst. 3 (9).
Pulido, F.J., Díaz, M., de Trucios, S.J.H., 2001. Size structure and regeneration of Spanish holm oak Quercus ilex forests and dehesas: effects of agroforestry use on their long-term sustainability. *Forest Ecol. Manage.*, 146(1-3), 1-13.
Rajora, O.P., Mosseler, A., 2001. Challenges and opportunities for conservation of forest genetic resources. Euphytica 118 (2), 197–212.
Rivas-Martinez, S., Penas, A., Diaz-González, T.E., Río, S.D., Cantó, P., Herrero, L., et al., 2014. Biogeography of Spain and Portugal. Preliminary typological synopsis. Int. J. Geobotanical Res.
Robredo, F., 1980. Tratamientos masivos con diflubenzuron contra la procesionaria del pino en España. Bol. Serv. Plagas 6 (2), 141–155.
Rockstrom, J., Gaffney, O., Rogelj, J., Meinshausen, M., Nakicenovic, N., Schellnhuber, H.J., 2017. A roadmap for rapid decarbonization. Science 355, 1269–1271.
Sabaté, S., Gracia, C.A., 2011. Water Processes in Trees: Transpiration and Photosynthesis. In: Birot, B., Gracia, C., Palahí, M. (Eds.), Water for forests and people in the Mediterranean region – a challenging balance. European Forest Agency, pp. 72-75.
Sampedro, V.C., 2006. Mejora genetica de *Pinus radiata* d. Don en Galicia (Doctoral dissertation, Universidade de Vigo).
Sánchez-Rodrıguez, F., Rodrıguez-Soalleiro, R., Español, E., López, C.A., Merino, A., 2002. Influence of edaphic factors and tree nutritive status on the productivity of Pinus radiata D. Don plantations in northwestern Spain. For. Ecol. Manage. 171 (1–2), 181–189.
San-Miguel-Ayanz, J., Camia, A., 2010. Forest fires, mapping the impacts of natural hazards and technological accidents in Europe. An overview of the last decade. In: EEA Technical Report No 13. European Environment Agency, Copenhagen.
Schwaiger, F., Poschenrieder, W., Biber, P., Pretzsch, H., 2019. Ecosystem service trade-offs for adaptive forest management. Ecosyst. Serv. 39, 100993.
Scott, D.F., Lesch, W., 1997. Streamflow responses to afforestation with *Eucalyptus grandis* and *Pinus patula* and to felling in the Mokobulaan experimental catchments, South Africa. J. Hydrol. 199, 360–377.
SECF, 2010. Situación de los bosques y del sector forestal en España. Sociedad Española de Ciencias Forestales (SECF). Available at: https://www.congresoforestal.es/fichero.php?t=12225&i=531&m=2185 [accessed May 2022].
Seijo, F., 2005. The politics of fire: Spanish forest policy and ritual resistance in Galicia, Spain. *Environ. Polit.* 14 (3), 380–402.
Serrada, R., 2000. Apuntes de repoblaciones forestales. Fundación Conde del Valle de Salazar-Escuela Universitaria de Ingeniería Técnica Forestal, Madrid.
Serrada, R., Montero, G., Reque Kilchenmann, J.A., 2008. Compendium of applied forestry in Spain. Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA), Madrid.
Serrada, R., Navarro, R.M., Pemán, J., 2005. La calidad de las repoblaciones forestales: una aproximación desde la selvicultura y la ecofisiología. Investigación agraria. Sistemas y recursos forestales 14 (3), 462–481.
Serrat, J.G., Segura, J.V., 2003. La evolución del paisaje forestal de la llanura del Vallés (Barcelona) hasta el siglo XII. Cuadernos de la Sociedad Española de Ciencias Forestales 16, 167–172.
Sing, L., Metzger, M.J., Paterson, J.S., Ray, D., 2017. A review of the effects of forest management intensity on ecosystem services for northern European temperate forests with a focus on the UK. Forestry 91 (2), 151–164.
Soto, A., Lorenzo, Z., Gil, L., 2007. Differences in fine-scale genetic structure and dispersal in *Quercus ilex* L. and *Q. suber* L.: consequences for regeneration of Mediterranean open woods. Heredity 99 (6), 601–607.
Soumare, A., Sall, S.N., Sanon, A., Cissoko, M., Hafidi, M., Ndoye, I., Duponnois, R., 2016. Changes in soil pH, polyphenol content and microbial community mediated by *Eucalyptus camaldulensis*. Appl. Ecol. Environ. Res. 14, 1–19.
Tasen, T., 2018. History of forest education in Europe 52-62. In: *Forestry and landscape management*. Kaunas Forestry and Environmental Engineering University of Applied Sciences.
Thomas, E., Jalonen, R., Loo, J., Boshier, D., Gallo, L., Cavers, S., Bozzano, M., 2014. Genetic considerations in ecosystem restoration using native tree species. For. Ecol. Manage. 333, 66–75.
UNEP, 2010. Strategic Plan for Biodiversity 2011–2020: Provisional Technical Rationale, Possible Indicators and Suggested Milestones for the Aichi Biodiversity Targets. UNEP/CBD/COP/10/27/Add.1. Available at: https://www.cbd.int/doc/meetings/cop/cop-10/official/cop-10-27-add1-en.pdf [accessed May 2022].
UNFCCC, 2015. The Paris Agreement Article 5 https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.
Vadell, E., de-Miguel, S., Pemán, J., 2016. Large-scale reforestation and afforestation policy in Spain: A historical review of its underlying ecological, socioeconomic and political dynamics. *Land Use Policy*, 55, 37-48.
Vadell, E., de Miguel, S., Fernández Centeno, G., Robla, E., Lerner, M., Pemán García, J., 2019. La forestación de tierras agrícolas: balance de un instrumento de política forestal para el cambio del uso de la tierra. Cuadernos De La Sociedad Española De Ciencias Forestales 45 (2), 1–20.
Van der Maaten-Theunissen, M., Schuck, A., 2013. Integration of Nature Protection in Forest Policy in the Netherlands. INTEGRATE Country Report. EFICENT-OEF, Freiburg.
Vanbeveren, S.P.P., Ceulemans, R., 2019. Biodiversity in short-rotation coppice. Renew. Sustain. Energy Rev. 111, 34–430.
Veiras, X., Soto, M.A., 2011. La conflictividad de las plantaciones de pino y eucalipto en España y Portugal. Greenpeace, p. 98.
Verkerk, P.J., Costanza, R., Hetemäki, L., Kubiszewski, I., Leskinen, P., Nabuurs, G.J., Potočnik, J., Palahí, M., 2020. Climate-Smart Forestry: the missing link. Forest Policy Econ. 115, 102164.
Viera, M., Ruíz Fernández, F., Rodríguez-Soalleiro, R., 2016. Nutritional prescriptions for Eucalyptus plantations: Lessons learned from Spain. Forests 7 (4), 84.
Vinceti, B., Manica, M., Lauridsen, N., Verkerk, P.J., Lindner, M., Fady, B., 2020. Managing forest genetic resources as a strategy to adapt forests to climate change: perceptions of European forest owners and managers. Eur. J. Forest Res. 139 (6), 1107–1119.
Williams, M.C., Wardle, G.M., 2007. *Pinus radiata* invasion in Australia: identifying key knowledge gaps and research directions. Austral. Ecol. 32, 721–739.
Zas, R., 2003. Interpretación de las concentraciones foliares en nutrientes en plantaciones jóvenes de *Pinus radiata* D. Don en tierras agrarias en Galicia. Invest. Agrar. Sist. Recur. For 12 (2), 3–11.
Zavala, M.A., Zamora Rodríguez, R., Pulido Díaz, F.J., Blanco Vaca, J.A., Imbert Rodríguez, J.B., Marañón, T., Valladares Ros, F., 2008. Nuevas perspectivas en la conservación, restauración y gestión sostenible del bosque mediterráneo. In: Valladares, F. (Ed.), Ecología Del Bosque Mediterráneo En Un MUndo Cambiante. Spanish Ministry of Environment and Rural and Marine Affairs, Madrid (Spain), pp. 511–532.
Zubizarreta, M., Arana-Landín, G., Cuadrado, J., 2021. Forest certification in Spain: Analysis of certification drivers. J. Cleaner Prod. 294, 126267.