



## Towards a common approach to defining forest management intensity

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### ABSTRACT

Forests play a crucial role in regulating the global climate, preserving biodiversity and providing essential ecosystem services; however, in the context of global change and anthropogenic pressures, it becomes ever more important to understand, evaluate and harmonize human interventions in forest ecosystems. Therefore, a comprehensive assessment of forest management practices is essential for promoting the sustainability and resilience of these systems. To this end, this study proposes a new index for assessing forest management intensity (FMI), which classifies forest management schemes on the basis of their demands. The values of the index are expected to range from 0, representing no management, to 3, indicating high-intensity management. The index comprises three factors: the degree of extractive impact on the ecosystem, the financial resources required and the input required from forest managers. In addition to conceptualization of the index, this work also presents a case study in which different examples of management schemes are evaluated, and the results confirm that management schemes requiring higher input, greater care and higher productive capacity yield higher values of the index than alternatives with longer rotations or lower productivity. Moreover, multifunctional systems demand more management input than traditional production systems for the same species. Furthermore, the study highlights that even old-growth forests, while minimally managed, require some level of attention, as abandonment of forests is associated with zero-intensity management. In conclusion, the FMI proves to be a valuable tool for assessing and comparing forest management practices at multiple scales (regional, national, and European), while highlighting the need for harmonized indicators to support coherent and informed decision-making in forest policy and sustainability planning. It is also possible to use each factor independently to provide insights into optimizing management strategies, by characterizing the management practices applied, and as a useful guide to developing more sustainable forestry approaches.

### 1. Introduction

According to definition proposed by the Food and Agriculture Organization of the United Nations (FAO, 2020), forest management brings together all of the processes of planning and implementing practices for the stewardship and use of forests to meet specific environmental, economic, social and cultural objectives. It includes all aspects directly linked to this activity, such as administrative, economic, legal, social,

technical and scientific details of the management of natural and planted forests. The purpose of forest management can range from simply meeting productive objectives, by generating socially or economically valuable goods and services, to actions aimed at safeguarding and maintaining forest ecosystems and their functions.

However, despite the key role of forest management in the conservation and sustainable use of forests, forest management schemes in different geographic and socioeconomic contexts are evaluated and

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classified in a variety of different ways (Duncker et al., 2012; Arano and Munn, 2006; Kahl and Bauhus, 2014; Schall and Ammer, 2013; Luysaert et al., 2011). This heterogeneity makes it difficult to quantify the intensity of forest management in an objective, comparable manner, tailored to different forest types and management methods.

### 1.1. State of the art

Several efforts have been made to classify and map forest management activities in Europe, but no standardized method has been agreed on due to the diversity of types of management. Duncker et al. (2012) proposed a conceptual framework for classifying forest management approaches in Europe, offering a structured basis for qualitative comparison of nature-reserve management, close-to-nature forestry, combined-objective forestry, intensive even-aged forestry and short-rotation forestry. Building on this, Hengeveld et al. (2012) and, more recently, Scherpenhuijzen et al. (2025) developed a forest management map of European forests, highlighting both the possibilities and limitations of continental-scale mapping. Scherpenhuijzen et al. (2025) also emphasized the current difficulty in defining forest management classes as they are not uniformly harmonized throughout Europe. Schulze et al. (2019) proposed a global mapping approach aimed at improving the spatial representation of forest management patterns, which also contributes to the European context.

In a study with the main objective of analysing management intensity among different types of landowners in Mississippi (USA), Arano and Munn (2006) took into account the system inputs and outputs; other objectives involved determining any differences in management schemes in relation to management activities and expenses. Other authors have focused on indices to characterize management intensity, by calculating the management index on the basis of the volume of harvested trees, the composition of tree species and the origin of dead wood (Kahl and Bauhus, 2014). The Silvicultural Management Intensity Indicator (SMI) developed by Schall and Ammer (2013) combines three main characteristics of a given stand: tree species, stand age and wood biomass (aboveground, live and dead) to represent i) the stand loss risk, which is a function of tree species composition and age, and ii) the stand density, which is a function of silvicultural regime, stand age and tree species. Alternatively, the Land Use and Disturbance Intensity (LUDI) (Luysaert et al., 2011) uses the relationship between stand density and diameter at breast height in a relatively untouched or pristine baseline forest, as well as various forest management strategies. This is used in combination with the self-thinning relationship to quantify the disparity between potential and actual biomass storage. Through this approach, the LUDI assesses the impact of different management schemes on forest biomass storage, enabling informed decisions in sustainable land use and development practices, and it is thus constrained to aboveground live biomass.

Other examples of different types of forest management intensity indexes have focused on quantifying the effects on biodiversity (Gossner et al., 2014; Liira and Sepp, 2009). In other situation, such as grasslands, land-use intensity (LUI) indexes have also been implemented (Blüthgen et al., 2012). Other more general indexes assess the intensity of land use based on inputs, outputs and the associated system level impacts of land-based production (e.g. changes in carbon storage or biodiversity) (Erb et al., 2013).

### 1.2. Conceptual framework and motivation for innovation in measuring forest management intensity

According to the definition of forest management (FAO, 2020), it is difficult to quantify each of the various components. However, forest management can be understood as the continuous effort made by managers to achieve the established objectives, taking into account all interventions and stand inputs throughout a complete management cycle.

Following this idea, forest management varies substantially across stands, forest types and regions, including methods inherited from our ancestors and also new management trends, ecological characteristics and technological contexts, among others. This variability creates a compendium of alternatives for a given species, main production (e.g. timber, biomass, resin, fruits, etc.) and site, in which not all will necessarily have the same management intensity. The intensity of forest management refers to the level of human intervention in a forest to achieve any objective (Bettinger et al., 2016). Building on this perspective, it makes sense to consider forest management intensity as a composite of several factors requiring effort from forest managers to modify natural processes, or to ensure or promote the maintenance of such processes. In this respect, forest management schemes can range from low intensity, where the natural dynamics of forest ecosystems are allowed to progress with minimal human intervention, to high intensity, where forests are managed intensively for specific purposes, such as timber production or biomass. In some cases, forests may also be managed for recreation, with varying degrees of intervention.

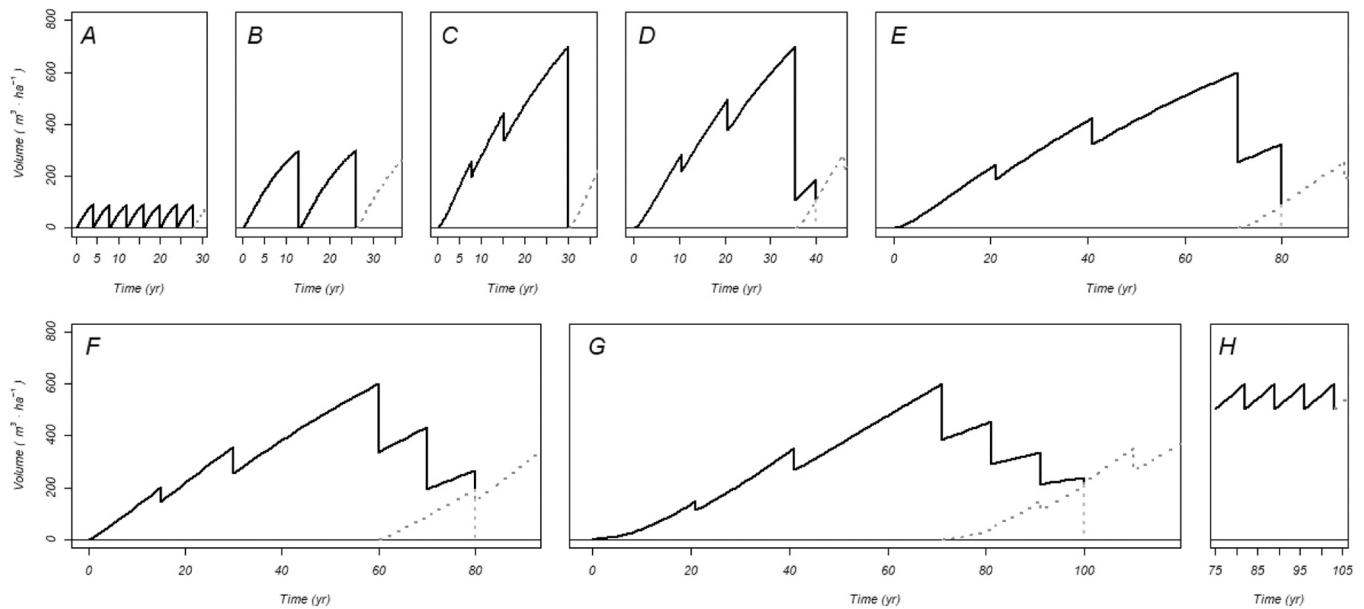
The diversity of factors involved in forest management, along with the different ways it can be manifested and measured, hampers standardized or universally applicable characterization (Scherpenhuijzen et al., 2025). Thus, for the purposes of territorial planning, forest management has traditionally been considered a categorical variable, generally with only two levels possible (management vs. non-management). However, some applications require more detailed characterization of the management intensity: for estimating the amount of human resources required to implement planned actions for a particular region; for optimizing intervention levels to maximize the provision of specific goods or ecosystem services; and for identifying the most suitable management schemes for areas with limited management capacity, among others.

Precise quantification of forest management intensity also provides valuable insights for refining the classification of management schemes based on their effects on biodiversity (Sertutxa et al., 2025a), stand composition (Sertutxa et al., 2025b), structural attributes (von Gadow and Hui, 2002; Zenner and Hibbs, 2000) and ecosystem functioning. It can also support forest certification processes, such as Forest Stewardship Council (FSC) and Program for Endorsement of Forest Certification (PEFC), by assessing compliance with sustainability standards, monitoring intervention levels and enabling comparison of different practices. Additionally, it may contribute to the characterization of low-impact silvicultural systems (LISS) (UKWAS, 2000) and provide a quantitative basis for audits and decision-making. These approaches raise a key question: how can different management schemes be compared in terms of management intensity? In the various harvesting methods represented in Fig. 1, it is assumed that extraction equals the average growth.

### 1.3. Goal and objectives

The goal of this study was to develop a comprehensive index for forest management that integrates ecological, economic and operational factors to facilitate decision-making and comparative analysis of different management schemes.

The need for a forest management index lies in having available a common framework for comparing management schemes based on the following items: i) harvest intensity; ii) investment by the forest owner; and iii) time dedicated to monitoring and maintenance. As has been shown, most of the indices developed so far in the field of forestry only assess the intensity of the crop extraction in order to study how the crop interacts with the environment in which it develops, and they generally overlook the managers' efforts. The index proposed here aims to include all perspectives of forest management (FAO, 2020; Bettinger et al., 2016), integrating the intensity of cultivation, environmental considerations and also the economic and temporal effort required from the forest owner and the forester to achieve the established objectives. In



**Fig. 1.** Graphical representation of forest management schemes with different types of harvest intervention and rotation: A) short rotation woody crop every 4 years, B) clear cutting every 13 years, C) pre-commercial thinning, thinning, and clear cutting at the end of 30 years, D) two-stage shelterwood method every 40 years, E) uniform two-stage shelterwood method every 80 years, F) three-stage shelterwood method every 80 years, G) four-stage shelterwood method every 100 years, and H) continuous cover forestry method with extraction every 7 years. The dotted lines indicate the continuation of the subsequent cycle. In cases where regeneration cuttings are applied, they represent the development of the new stand emerging under the canopy openings created by the regeneration cuts implemented.

this sense, its development is intended to be carried out in a manner conceptually similar to Life Cycle Assessment (LCA; EN ISO 14040, 2009), which provides a harmonized framework for assessing the inputs, outputs, and environmental impacts of systems with wide differences in structure and intensity.

Another key objective that has motivated the development of this index is to produce a method with the capacity to measure forest management intensity and compare it with the provision of goods such as timber production, carbon sequestration, biodiversity and other ecosystem services. Furthermore, the index could serve as a tool for territorial planning and for characterizing forest management intensity on the basis of the value of each factor, while also providing a quantitative basis for audits and decision-making. The new EU forest strategy for 2023 (European Commission, 2021) highlights the socio-economic functions of forests for thriving rural areas and boosting forest-based bio-economy within sustainability boundaries stating the need for comprehensive forest monitoring and reporting. Recent legislation considers these aspects important: The Nature Restoration Law (European Parliament and Council of the European Union, 2024) and the proposed Regulation on a monitoring framework for resilient European forests (European Commission, 2023). Furthermore, the Status of Europe's Forest (SoEF, FOREST EUROPE) since 1998, has provided a common approach to defining Sustainable Forest Management by identifying Criteria and Indicators on which European members must report. The average values of the proposed indicator in certified forests, weighted by forest area, are suggested to contribute relevant information that could be included in Criterion 6 (Socioeconomic functions).

## 2. Materials and methods

This section is divided into two parts: in the first, the theoretical development of the forest management index is explained, and in the second, the index is applied to a case-study comparing different management schemes in Spain.

### 2.1. Development of the forest management intensity index

Three factors were defined for inclusion in the forest management intensity index, all of which were hypothesized to be directly related to the extent of forest management and complementary regarding the nature of the management indicator: i) harvest intensity (HI), ii) economic inputs to the system (I), and iii) the time spent by the manager implementing the management scheme (E). These factors are assumed to be uncorrelated across all possible management schemes, as large or significant values of HI are expected for some schemes when I and E are small (i.e. non selective logging in tropical forests with natural regeneration), large values of I are expected when HI is null and E takes intermediate values (i.e. peri-urban forests), and large values of E are expected when HI and I are small (i.e. strict conservation). However, the values of HI, I and E may be correlated for most common management schemes, e.g. having a large stand timber yield (large HI value) usually requires investing in the stand (large I value) and is time consuming for the manager (large E value).

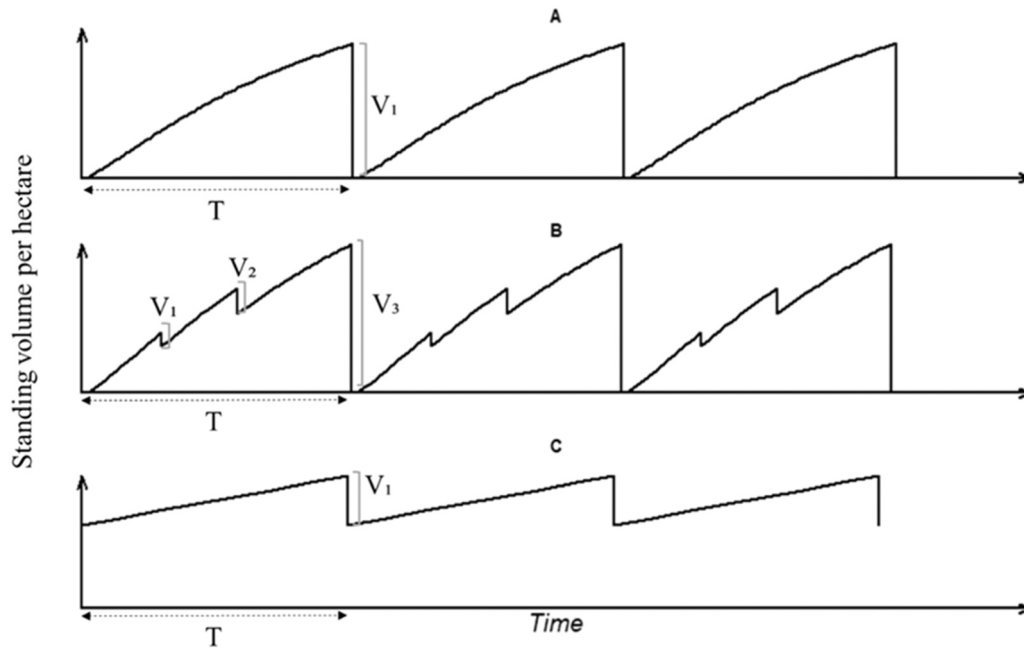
In the following, the indicators for each factor are explained.

#### 2.1.1. Harvest intensity (HI)

Harvest intensity (HI) is defined as timber harvest over a complete management cycle, in which all silvicultural interventions are considered (Fig. 2). This factor refers to timber harvests and not to potential growth or yield, and applies to management alternatives where the main stand is completely removed (clear cutting, Figs. 2A and 2B) and also to continuous cover forestry (Fig. 2C). The indicator used for HI is calculated as shown in Equation [1],

$$HI = \frac{\sum_{i=1}^n V_i}{T} \quad (1)$$

where HI ( $\text{m}^3 \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$ ) is Harvest Intensity,  $V_i$  is the harvested timber volume per hectare for each  $i$  management interventions within a given cycle ( $\text{m}^3 \cdot \text{ha}^{-1}$ , see Fig. 2) and  $T$  is the duration of the management cycle (years), as shown in Fig. 2.



**Fig. 2.** Graphical representation of standing volume per hectare for different management practices, showing different harvest intensities and frequencies: A) clear cutting: a growth pattern followed by total harvest in each cycle, B) thinning with final clear cutting: a series of minor interventions followed by a final harvest, C) continuous cover forestry: the standing volume remains more stable with smaller, periodic interventions.  $V_i$  corresponds to the harvested volume at intervention  $i$  within the management cycle ( $T$ ).

2.1.2. Economic inputs ( $I$ )

The economic inputs include those of all those interventions aimed at interfering with natural processes in the system with the objective of maximizing the consecution of management objectives. These include, for example, the use of improved genetic material, pruning, enhanced regeneration, fertilization, pest and disease control, control of competing vegetation, and risk management (Fig. 3). The hypothesis underlying consideration of this factor is that more management will be required as the inputs to the system increase. Due to the diverse nature of the possible inputs, this factor is quantified in economic terms by using the land expected cost (USD·ha<sup>-1</sup>), which is defined as the net present value of all future net costs across infinite management cycles. Estimation of  $I$  is based on the net present cost (NPC) of all forestry operations in a cycle and discounted at the beginning of the cycle, as shown in Equation [2],

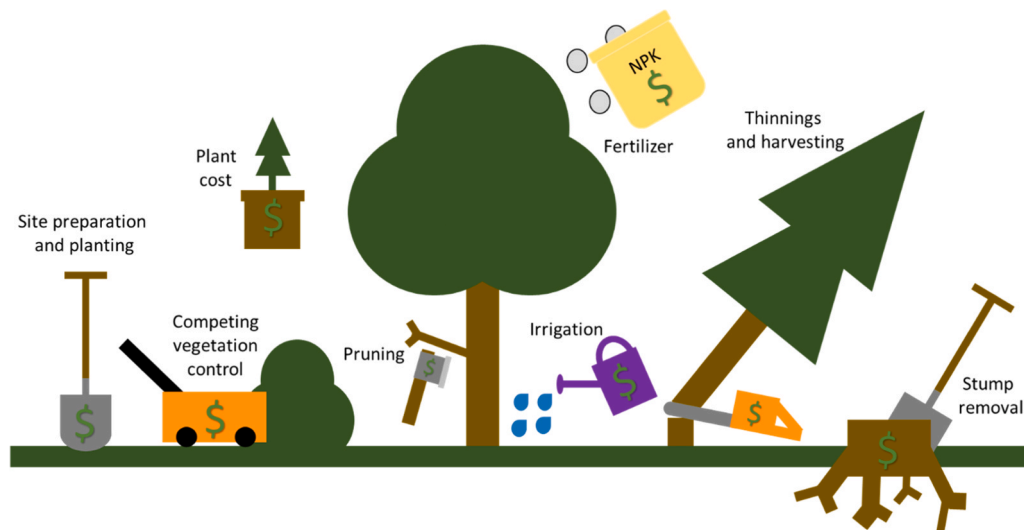
$$NPC = \sum_{t=0}^T \frac{|X_t|}{(1+r)^t} \tag{2}$$

where  $NPC$  is the net present cost (USD·ha<sup>-1</sup>),  $X_t$  (USD·ha<sup>-1</sup>) are the intervention costs at age  $t$  (years) within a given cycle  $T$  (years),  $r$  is the discount rate (fixed at 3% for this case-study).

The  $NPC$  of an infinite series of cycles is therefore defined through the expected cost of land, which serves as the specific measure of  $I$  (USD·ha<sup>-1</sup>), the value of which is calculated as shown in Equation [3]:

$$I = \frac{NPC}{1 - \frac{1}{(1+r)^T}} \tag{3}$$

where  $NPC$  is the net present cost (USD·ha<sup>-1</sup>),  $r$  is the discount rate



**Fig. 3.** Graphical representation of some examples of economic inputs ( $I$ ) to the forest stand by forest managers.

(fixed at 3 %) and  $T$  is the length of the management cycle (years).

This approach is based on an expression used to calculate the expected land value ( $ELV$ ), which enables the profitability of a particular aspect of forest management to be taken into account (Borges et al., 2014); however, in this case only the costs of the operations are taken into account and the benefits are not considered. Monetary values, originally collected in euros (EUR), were converted into constant 2022 U.S. dollars (USD) using the average annual official exchange rate reported by the World Bank (1 EUR = 1.053 USD; World Bank, 2023), which is widely used in macroeconomic analyses.

### 2.1.3. Time spent ( $E$ )

The last factor is the time spent by the manager to implement the planned scheme ( $E$ ), which includes planning, surveillance prior to decision-making, administrative procedures, contracting or tendering and monitoring field work in each intervention. The variable used as a proxy is the work undertaken by the manager to implement the management plan, measured as the number of management events (interventions or stand entries) throughout a cycle, weighted by the time (hours) consumed by the manager in each intervention. This approach is based on defining the total number of interventions necessary to implement the management scheme ( $m$ ) and weighting each  $j$  intervention by considering the planning efforts, contracting or tendering, and monitoring efforts, among others (see columns in Table 1). The value of  $E$  ( $\text{h}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ ) is estimated by Equation [4]:

$$E = \frac{\sum_{j=1}^m w_j}{T} \tag{4}$$

where  $m$  is the total number of interventions in a  $T$  management cycle (years) and  $w_j$  is the value of each  $j$  intervention weighted by considering the elements shown in columns in Table 1.

The activities listed in Table 1 are defined as follows: management planning (strategic planning) is the drafting and updating strategic guidelines for forest use and care; plantation refers to planning and

coordinating tree planting operations; plant replacement involves organizing and supervising the replanting of failed or dead trees; competing vegetation control refers to planning and monitoring measures to suppress undesirable vegetation; protection against game damage refers to designing and overseeing strategies to prevent wildlife harm; fertilization involves scheduling and managing nutrient application programs; pre-commercial thinning refers to planning early thinning operations to enhance forest structure; phytosanitary care involves coordinating disease and pest prevention and response protocols; training pruning refers to defining criteria and timing for shaping young trees; high pruning refers to planning the removal of lower branches to meet quality objectives; tree selection involves establishing guidelines for choosing which trees to retain or harvest; irrigation refers to organizing and monitoring water supply systems for tree growth; thinning refers to planning the selective removal of trees; final clear cutting involves preparing and authorizing the complete harvest of a forest stand; stump removal involves coordinating the extraction of stumps post-harvest; forest fuel management consist of reducing or modifying vegetation to decrease wildfire risk and intensity; ecosystem maintenance refers to defining strategies to preserve ecological functions; species reintroduction refers to planning and overseeing the reintroduction of native species; recreational activities involve designing and regulating public recreational use of forests; educational activities refer to planning and managing forest-based educational programs; social awareness refers to developing and implementing outreach and communication strategies; protective actions refer to identifying and supervising conservation-oriented interventions; eradicating IAS refers to coordinating removal plans for invasive alien species; legal aspects refer to ensuring compliance and administrative alignment with forestry laws, as well as conflict resolution; research activities refer to planning and supporting scientific studies in the forest; surveillance refers to organizing systems for regular monitoring and early detection; and inventory refers to managing data collection and analysis of forest resources.

The weighting process includes some degree of flexibility for quantifying the management time for similar interventions across different

**Table 1**

Weights ( $\text{hours}\cdot\text{ha}^{-1}$ ) proposed for the most common interventions or stand entries collected from the management schemes under study (see Table 2).

Intervention or stand entries	Planning	Surveillance prior to decision-making	Administrative procedures	Contracting / Tendering	Monitoring / Control of interventions	Total weight ( $w_j$ )
Management planning	3	1	2	1	1	8
Plantation	2	2	1	1	2	8
Plant replacement	0	1	0	1	2	4
Competing vegetation control	0	1	0	1	1	3
Protection against game damage	2	1	0	2	1	6
Fertilization	2	1	0	1	1	5
Pre-commercial thinning	0	1	1	1	1	4
Phytosanitary care	0	2	1	1	3	7
Training pruning	0	2	0	1	1	4
High pruning	0	2	0	1	1	4
Tree selection	0	2	0	1	1	4
Irrigation	3	2	1	1	3	10
Thinning	2	3	2	1	3	11
Final clear cutting	2	2	2	1	2	9
Stump removal	0	1	0	1	1	3
Forest fuel management	0	1	0	1	1	3
Ecosystem maintenance	2	3	1	1	3	10
Species reintroduction	1	2	1	1	2	7
Recreational activities	0	0	2	1	1	4
Educational activities	1	0	1	0	0	2
Social awareness	1	0	1	1	1	4
Protective actions	1	3	1	1	3	9
Eradicating IAS	1	3	1	1	3	9
Legal aspects	0	1	2	1	1	5
Research activities	1	0	2	0	1	4
Surveillance	1	0	2	1	1	5
Inventory	1	0	2	0	0	3

species, sites, or administrative units (among others), as not all elements shown in the columns in Table 1 will have the same weight in such circumstances. The weights have been established based on previous experience of experts applying management schemes in the Spanish legal and administrative context. While the process conducted by experts involves a degree of subjectivity, this approach was chosen due to the lack of viable objective alternatives reported in the literature that can adequately capture the variations across species, sites, administrative units, and, particularly, across different national contexts in which the interventions are carried out. Differences in local conditions and legislation in each country may influence the relevance and weight of some factors, or even include new aspects, justifying the use of a flexible and adaptive approach for calculating management time. For example, while logging permits or management planning may be compulsory in some regions, they may not be required in another. It is essential that the weights are defined within the same legal and administrative context to ensure their validity and comparability.

#### 2.1.4. Forest management intensity index (FMI)

Each of the factors defined has different units (HI  $\text{m}^3 \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$ , I  $\text{USD} \cdot \text{ha}^{-1}$  and E  $\text{h} \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$ ), and the numerical values may differ greatly among factors. In order to be able to include all of these in the FMI, the values of each factor must be standardized, as shown in Equation [5]. Each factor yields a value of 0 for no management and of 1 for the highest management intensities.

$$F_{S_k} = \frac{F_k}{F_{kREF}} \quad (5)$$

where  $F_{S_k}$  is the standardized value for the  $k$  factor (either HI, I or E),  $F_k$  is the unstandardized value for the  $k$  factor and  $F_{kREF}$  is the reference value for the factor  $k$ .  $F_{kREF}$  corresponds to the maximum value reached by each factor for the management schemes analysed in this study (Table 2). Defining a unique value of  $F_{kREF}$  for each factor enables comparison of the management intensity across contrasting management schemes, species and sites.

Finally, all factors are combined into a single, dimensionless FMI by summing the standardized values of the three factors, as shown in Equation [6]. This approach yields values ranging from 0 (no management) to 3 (highest intensity), where equal weight is assigned to each factor, as they are considered complementary and equally important components of forest management intensity.

$$FMI = HIs + Is + Es \quad (6)$$

where FMI is the value of the management intensity index (dimensionless), and HIs, Is and Es are the standardized values of the factors as shown in Equation [5].

#### 2.2. Case study of the use of the forest management intensity index: management schemes considered

The case study aims to cover the widest possible range of values for the factors HI, I and E, and combinations of these for forest management schemes in Spain. The wide variability in climate conditions in Spain (ranging from maritime to intermediate and continental subtropical climate) (European Environment Agency, 2012), as well as in tree species, management objectives (Serrada et al., 2008), harvest intensity and frequency (Suvanto et al., 2025) and forest management classes (Scherpenhuijzen et al., 2025) together create an interesting situation for testing the performance of the FMI. The management schemes considered in the case study are listed in Table 2 and are described in more detail below.

PX1: One of the models used was the poplar (*Populus* sp.) short rotation biomass crops in Mediterranean environments, although this is not yet a commercial reality. The idea behind considering this model to test the FMI is that the short duration and productivity of the rotations (Venendaal et al., 1997), as well as the high requirement for inputs throughout its cultivation, such as irrigation (Oliveira et al., 2020; Fuertes et al., 2021), provide a clear example in which most factors reach high values, implying a high level of management input. Therefore, this scheme has attempted to include all possible interventions to simulate high management intensity. Likewise, Spain was chosen because productivity is expected to be higher (Pérez-Cruzado et al., 2014) than in other European countries, due to the climatic, edaphic and demographic characteristics of some parts of the country. A 4-year rotation length was considered, with an average potential production at a national level in Spain estimated at  $43.71 \text{ m}^3 \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$  assuming a moisture content of 50 % and green wood density of  $700 \text{ kg} \cdot \text{m}^{-3}$  (Oliveira et al., 2020). The initial planting density was established at 10,000 cuttings  $\cdot \text{ha}^{-1}$ , with the need to control pests (if necessary) and competing vegetation, including pre- and post-emergence weed control, and mechanical control if necessary, during the first years of establishment, as well as irrigation (Biomasa, 2007; Mitchell et al., 1999; Fuertes et al., 2021). A crop is obtained by coppicing every 4 years. After three rotations, the stools are removed by chemical treatment or by mechanical grinding, and the land is deep-ploughed and disced before replanting with clonal cuttings. For this reason, factors I and E were calculated for 3 rotations (12 years).

PX2: For poplar plantations to generate peeled veneer as the main product, the average production rate of average quality wood of  $24.5 \text{ m}^3 \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$  was selected, along with a rotation length of 13 years, which is the average length of the rotations (10–16 years) generally used (Sixto et al., 2008). The following main factors were extracted from the literature: planting density of 277 trees  $\cdot \text{ha}^{-1}$ , a *Populus x generosa* Henry clone with a cost of 2.03 USD  $\cdot \text{rod}^{-1}$  of 4–5 m in height, implementation

**Table 2**  
Main information of the management schemes considered in the case study.

Code	Species	Management scheme	Main objective	Cycle (years)	Forest Management Approach (Duncker et al., 2012)
PX1	<i>Populus</i> sp.	Short rotation biomass crops	Biomass	4	Short-rotation forestry
PX2	<i>Populus x generosa</i>	Plantation with final clear cutting	Peeled veneer	13	Short-rotation forestry
EN1	<i>Eucalyptus nitens</i>	Plantation with final clear cutting	Pulpwood	14	Short-rotation forestry
EN2	<i>Eucalyptus nitens</i>	Plantation with one thinning and final clear cutting	Sawn timber	25	Intensive even-aged forestry
PR1	<i>Pinus radiata</i>	Plantation with final clear cutting	Pulpwood	23	Intensive even-aged forestry
PR2	<i>Pinus radiata</i>	Plantation with thinnings and final clear cutting	Sawn timber	32	Intensive even-aged forestry
PS1	<i>Pinus sylvestris</i>	Plantation with thinnings and final clear cutting	Timber	80	Intensive even-aged forestry
PSY	<i>Pinus sylvestris</i>	Uniform shelterwood method	Sawn timber	100	Combined objective forestry
FS1	<i>Fagus sylvatica</i>	Uniform shelterwood method	Wood and timber	120	Combined objective forestry
FS2	<i>Fagus sylvatica</i>	Continuous cover forestry	Multi-objective	10	Close to nature forestry
QP1	<i>Quercus pyrenaica</i>	Uniform shelterwood method	Firewood & Timber	100	Combined objective forestry
FA1	<i>Fagus sylvatica</i> & <i>Abies alba</i>	Old growth forest	Conservation	1	Nature-reserve management

of the plantation consisting on levelling and subsoiling, a total of 10 mechanical tillage operations such as disc harrowing and cultivation to control competing vegetation, use of fertilizer N50/P30/K100 depending on soil requirements, pest control (if necessary), formative pruning, cleaning pruning of the stem yearly for 3–6 years and up to 6–8 m high, annual competing vegetation control until age 6 and then biennially, annual irrigation of  $4000 \text{ l}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$  (as this case refers to a shallow-rooted plantation, whereas deep-rooted plantations do not require irrigation), with final clear cutting and stump removal, either by overturning and burying during replanting operations or by chemical treatment prior to the establishment of the new plantation (Biomasa, 2007; Sixto et al., 2008).

EN1: The eucalyptus (*Eucalyptus nitens* Deane & Maiden) management scheme for pulpwood was considered from among those approved for the autonomous community of Galicia (Xunta de Galicia, 2021), assuming the following: a 14-year rotation as age of maximum volume production, 1428 trees·ha<sup>-1</sup>, planting with genetically improved seedlings at a cost of 0.29 USD·plant<sup>-1</sup>, plant replacement, 2 mechanical and manual controls of competing vegetation per rotation, implantation fertilization with NPK 8/24/16 and a dose of 50 gr and maintenance fertilization with 500 gr·plant<sup>-1</sup> of NPK 1/1/1, with final clear cutting. The productivity of  $23.0 \text{ m}^3\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$  was estimated using dynamic models for the species and a site index of 16 m (Diéguez-Aranda et al., 2012).

EN2: When sawn timber production is the main objective of *Eucalyptus nitens* Deane & Maiden plantations, the initial density is around 1111 trees·ha<sup>-1</sup>, the rotation length is increased to 25 years, pre-commercial thinning is recommended up to 500–600 trees·ha<sup>-1</sup>, high pruning to 6 m in the 150–200 final trees·ha<sup>-1</sup> and thinning the other trees (Xunta de Galicia, 2021). The other aspects are shared with EN1. The productivity obtained from the same way as EN1 was in this case  $23.2 \text{ m}^3\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$  (Diéguez-Aranda et al., 2012).

PR1: The radiata pine (*Pinus radiata* D. Don) management scheme for pulpwood was extracted from those approved for the autonomous community of Galicia (Xunta de Galicia, 2021), assuming the following: a 23-year rotation with final clear cutting, an initial density of 977 trees·ha<sup>-1</sup> and training pruning at early stages to improve stem form. Plant replacement and competing vegetation control are carried out during the establishment phase. Thinning is performed once between ages 10 and 15, removing 30–50 % of the stems in a semi-systematic manner, leaving approximately 500–600 trees·ha<sup>-1</sup>. The productivity of  $13.0 \text{ m}^3\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$  was estimated using dynamic models for the species and a site index of 21 m (Diéguez-Aranda et al., 2012).

PR2: When the main objective is sawn timber, the initial density for radiata pine is 857 trees·ha<sup>-1</sup>, and the rotation is extended to 32 years. Plant replacement and competing vegetation control are also implemented at early stages. Formative pruning can be applied up to 1 m in the first 5 years, followed by low pruning to 2.5–3 m once the mean diameter reaches 10 cm. High pruning is performed up to 6 m on the 250–300 best trees·ha<sup>-1</sup>. Initial thinning is carried out between ages 10 and 15 years, removing 30–50 % of the stems (considering windthrow risk), leaving 500–600 trees·ha<sup>-1</sup>. A second thinning may be carried out between ages 15 and 25, extracting 30–35 % of the remaining stems to reach 250–300 trees·ha<sup>-1</sup> (Xunta de Galicia, 2021). The productivity was  $13.1 \text{ m}^3\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ , for a site index of 21 m (Diéguez-Aranda et al., 2012).

PS1: The summary of the management scheme of Scots pine for timber includes the following aspects: an 80-year cycle as age of maximum volume production, a productivity of  $12.1 \text{ m}^3\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ , from the average between high and low site quality from the production tables of Scot pine in Spain (Rojo-Alboreca and Montero, 1996). The initial density is about 1500 trees·ha<sup>-1</sup> (Xunta de Galicia, 2021) and the final density is about 200 trees·ha<sup>-1</sup>. Two applications of competing vegetation control are required during the rotation period, as well as tree selection, low and high pruning, five thinning treatments and tree retention cuttings (Montero et al., 2008).

PSY: Following uniform successive thinning scheme for Scots pine, with the primary objective of producing sawn timber, the average growth over a rotation period of 100 years is approximately  $6.0 \text{ m}^3\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$  (Montero, 1994). Plantation establishment is not necessary, as natural regeneration can be applied, with only plant replacement required in case of regeneration failure. The ideal initial stocking density is around 3000 trees·ha<sup>-1</sup>, followed by a thinning and five subsequent selective thinnings, progressively reducing the stand density to 200 trees·ha<sup>-1</sup> before the final harvest at the end of the regeneration period. To ensure proper maintenance and achievement of the final objective, control of competing vegetation is carried out three times during the early years of the stand, along with tree selection and both low and high pruning operations (Montero et al., 2008).

FS1: The beech (*Fagus sylvatica* L.) management scheme for wood and timber is characterized by a natural regeneration of the stand, and some tending operations devoted to reducing competition from other plants is required. Control of competing vegetation is also required, especially pre-commercial thinning. Trees that are in good condition before thinning are selected. The harvesting method includes nine thinnings with final tree retention cuttings to improve regeneration and a 120-year rotation length (Madrigal et al., 2008). The productivity is  $3.9 \text{ m}^3\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$  estimated using static models for beech in Navarra (Spain) (Madrigal et al., 1992).

FS2: The prescriptions for beech forests with close-to-nature management are characterized by periodic selective thinning based on harvestability criteria. This model begins with an already irregular forest stand (Madrigal et al., 2008), followed by identical cycles with an average extraction of approximately  $37.5 \text{ m}^3\cdot\text{ha}^{-1}$  every 10 years (Sabín-Galán et al., 2013). In addition to thinning, underbrush removal and tree selection are also performed every 10 years.

QP1: Pyrenean oak (*Quercus pyrenaica* Willd.) scheme for firewood and timber through uniform shelterwood method includes an initial density of 2500 trees·ha<sup>-1</sup>, a rotation length of 100 years, and a productivity of about  $3 \text{ m}^3\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$  according to average site quality (Xunta de Galicia, 2021). The main treatments include mechanical cleaning, street opening, pre-commercial thinning to 1600 trees·ha<sup>-1</sup> and seven thinnings with final tree retention cuttings to improve regeneration from 100 trees·ha<sup>-1</sup> (Xunta de Galicia, 2021).

FA1: This model corresponds to an example of old-growth forest where beech is co-dominant with silver fir (*Abies alba* Mill.) within the Integral Reserves of Lizarzoia and Aztaparreta (Martin-Benito et al., 2022; Molina-Valero et al., 2021). The primary objective is conservation, and there is therefore no production goal and no extractions are carried out. To determine the FMI, the activities performed by the managers over an average year were briefly summarized for the entire area under that protection status (Government of Navarra, 1998). The tasks associated with these protected areas are related to regulation of access and administrative procedures, as well as supervision of research conducted within the Reserves and monitoring. Additionally, some actions carried out by forest rangers, such as censuses and inventories, as well as the delimitation and signage of the area, were also considered.

### 2.3. Estimation of values of HI, I and E in the case-study

The values of HI were assigned to each management scheme by using yield tables (PX2, PS1, PR1, PR2, EN1, EN2 and FS1) (Sixto et al., 2008; Rojo-Alboreca and Montero, 1996; Diéguez-Aranda et al., 2012; Madrigal et al., 1992) by considering the mean site conditions for these species in Spain or the reference literature (PX1, PSY, FS2 and QP1) (Oliveira et al., 2020; Montero, 1994; Sabín-Galán et al., 2013; Xunta de Galicia, 2021). The values of *T* were obtained for each management scheme considered either the rotation of maximum volume production (those where the mean increment is maximum, for PS1, PR1 and EN1) or the recommended rotation length in the literature (PX1, PX2, EN2, PR2, PSY, FS1, FS2 and QP1) (Oliveira et al., 2020; Sixto et al., 2008; Xunta de Galicia, 2021; Montero, 1994; Madrigal et al., 2008; Sabín-Galán

et al., 2013).

The values of I were assigned to each management scheme by using the official unitary prices database for forestry operations in Spain (TRAGSA, 2022) (see Table A1). This is the reference database for contracting and tendering public and private projects in Spain and is an exhaustive compendium of work for forestry operations. Due to the specificity of PX1 treatments, the average costs presented in the economic analysis by Fuertes et al. (2021) were used.

The values of E were assigned to each management scheme by considering all management interventions that consume time by the manager across a management cycle. The interventions and stand entries considered for each management scheme, as well as the number of times the element in columns is required across the management cycle are summarized in Table 3. The interventions range from standard forestry practices such as plantation establishment, plant replacement, thinning and pruning, to additional actions such as fertilization, irrigation, inventory, surveillance or tree selection.

After multiplying the column of weights of each intervention (Table 1) and the number of times each intervention is repeated or not (Table 3), the total number of hours throughout a rotation for each of the management scheme can be obtained by summing all weighted interventions (Eq. 4). Finally, this number of hours is divided by the duration of the rotation to enable comparison, except for the FA1 model, where it was divided by the total area of the Integral Reserves (239.4 ha), because the number of stand entries for an average year was summed in these protected areas.

### 3. Results

#### 3.1. Development of the forest management intensity index and reference values for factors HI, I and E

The values of the three factors obtained along with the years of rotation length considered for each management scheme are shown in Table 3.

The duration of the rotations ranged from 4 years in PX1 to 120 years

in FS1 with productive purposes (Table 4). Maximum values of all three factors were obtained in the PX1 management scheme. The lowest values of HI and I were reached in FA1. The lowest value of E was obtained in the PSY management scheme.

To standardize the FMI, the maximum values of HI, I and E were considered for defining  $HI_{REF}$ ,  $I_{REF}$ ,  $E_{REF}$  (see Equation [5] and Table 4). The values were  $43.71 \text{ m}^3 \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$  for  $HI_{REF}$ ,  $33,568.19 \text{ USD} \cdot \text{ha}^{-1}$  for  $I_{REF}$  and  $19.83 \text{ h} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$  for  $E_{REF}$ . In this case study, they were reached by PX1. Applying the previously mentioned values, the FMI formula is as follows (Eq. 6):

$$FMI = \frac{HI}{43.71} + \frac{I}{33,568.19} + \frac{E}{19.83} \tag{6}$$

#### 3.2. Case study

In addition, the previously conceptualized index was tested with different case studies, grouping all the treatments and activities that are

**Table 4**  
Values obtained for each of the factors included in the index.

Management scheme	Cycle (years)	HI ( $\text{m}^3 \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$ )	I ( $\text{USD} \cdot \text{ha}^{-1}$ )	E ( $\text{h} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$ )
PX1	4*	43.71	33,568.19	19.83
PX2	13	24.50	27,497.47	16.69
EN1	14	22.96	18,720.82	2.86
EN2	25	23.22	10,888.11	2.52
PR1	23	13.00	5935.81	2.04
PR2	32	13.10	6234.07	2.19
PS1	80	12.10	6975.72	1.36
PSY	100	6.00	3298.76	1.01
FS1	120	3.90	3076.05	1.26
FS2	10	3.75	1854.60	2.70
QP1	100	3.00	1166.70	1.04
FA1	1	0.00	579.27	1.74

\*Extractions are carried out every 4 years, while planting is conducted once every 12 years, taking advantage of the regrowth of the initial plantation in the intermediate cycles.

**Table 3**  
Number of interventions or stand entries for each management scheme.

Interventions or stand entries	PX1	PX2	EN1	EN2	PR1	PR2	PS1	PSY	FS1	FS2	QP1	FA1
Management plan	1	1	1	1	1	1	1	1	1	1	1	1
Plantation establishment	1	1	1	1	1	1	1	0	0	0	0	0
Plant replacement	0	1*	1	1	1	1	1	1	0	0	0	0
Competing vegetation control	12	9	2	2	1	1	3	3	1	0	2	0
Protection against game damage	0	0	0	0	0	0	0	0	0	0	0	0
Fertilization	3*	1*	1	1	0	0	0	0	0	0	0	0
Pre-commercial thinning	0	0	0	1	0	0	1	1	1	1	1	0
Phytosanitary care	3*	1*	0	0	0	0	0	0	0	0	0	0
Training pruning	0	3	0	0	1	2	1	1	0	0	0	0
High pruning	0	1	0	1	0	1	1	1	0	0	0	0
Tree selection	0	0	0	1	0	1	1	1	7	1	0	0
Irrigation	12	13	0	0	0	0	0	0	0	0	0	0
Thinning	0	0	0	1	1	2	5	5	9	1	7	0
Final clear cutting	3	1	1	1	1	1	1	1	1	0	1	0
Stump removal	1	1	0	0	0	0	0	0	0	0	0	0
Forest fuel management	0	0	0	0	0	0	0	0	0	0	0	0
Ecosystem maintenance	0	0	0	0	0	0	0	0	0	0	0	0
Species reintroduction	0	0	0	0	0	0	0	0	0	0	0	0
Recreational activities	0	0	0	0	0	0	0	0	0	0	0	60
Educational activities	0	0	0	0	0	0	0	0	0	0	0	60
Social awareness	0	0	0	0	0	0	0	0	0	0	0	1
Protective actions	0	0	0	0	0	0	0	0	0	0	0	0
Eradicating IAS	0	0	0	0	0	0	0	0	0	0	0	0
Legal aspects	0	0	0	0	0	0	0	0	0	0	0	4
Research activities	0	0	0	0	0	0	0	0	0	0	0	2
Surveillance	0	0	0	0	0	0	0	0	0	0	0	2
Inventory	0	0	0	0	0	0	0	0	0	0	0	2
Total number of interventions or stand entries	36	33	7	11	7	11	16	15	20	4	12	132

\*If necessary

recommended for each species and management scheme. It was possible to obtain the values for the proposed case studies by following the index methodology and equations.

The highest FMI value corresponded to PX1 and was much higher than the next scheme, while the lowest value corresponded to FA1 (Fig. 4). Although the rotation length was very similar in EN1 and PX2 (Table 4), the HIs value was very similar, although Is and Es are higher in PX2. Comparison of PX2 and EN2 showed that PX2 yielded a value that almost twice that of EN2, despite there being little difference in terms of HIs. Notably, the Is value for FA1 was quite low despite the existence of some management costs.

#### 4. Discussion

##### 4.1. Development of the forest management index

Development of the FMI is a basic, multidimensional process, particularly in the context of current global challenges such as climate change, biodiversity loss and the need for sustainable resource management. This index provides a systematic and objective framework for assessing and monitoring forest management intensity, considering aspects such as the extraction of forest products, the economic investment, and the time required for forest objective to be achieved. Conceptually, the FMI is similar to life cycle assessment (LCA), aiming to enable meaningful comparisons across forest types and management systems that differ widely in structure, function and management intensity. Defining its system boundaries, the FMI begins with site-preparation processes and ends at the forest road, encompassing all relevant primary and secondary operations throughout the forest product chain, as recommended in standardized life-cycle assessment methodologies (Klein et al., 2015).

Another interesting perspective to consider is the inclusion of a fourth factor in the index to reflect the degree of ecosystem alteration, as proposed by Tschardt et al. (2005). This aspect can be analysed using the proposed index, enabling a more comprehensive assessment of land use intensity, in line with studies such as those by Erb et al. (2013). Furthermore, this relationship could be explored by linking FMI to other approaches that characterize forest structure and diversity, such as those

proposed by von Gadow and Hui (2002) and Zenner and Hibbs (2000).

Regarding the factors considered in the development of this index, the first factor HI is consistent with the first component of the *ForMI* developed by Kahl and Bauhus (2014), in which it is the proportion of harvested tree volume (*Iharv*). In this case, the authors calculated *Iharv* as the ratio of harvested volume to the sum of standing, harvested and dead wood volume. Recently, Suvanto et al. (2025) used the total harvest rate, which includes the frequency and intensity of harvesting events, defined as the percentage of the total basal area of the tree in the grid cell that was harvested annually, to assess harvesting intensity and frequency. However, the HI factor only reflects the volume of wood extracted without considering the total volume produced in the stand, as the harvesting effort is proportional to the volume of wood extracted. This approach produces a variable that is easier to quantify at the end of the cycle without requiring an exhaustive inventory while also enabling evaluation of how extractive the management scheme is concerning the environment that supports it.

Another reason that the extraction ratio has not been used is because evaluating the total extraction ratio of a complete long-term cycle is a complex process. It requires information about the volume of dead wood throughout the entire cycle, which implies carrying out numerous inventories to prevent that dead wood from decomposing and going unnoticed in a single inventory at the end of the rotation. This ratio can be valuable when carrying out specific evaluations of the degree of management intensity of a forest or a specific intervention.

Despite the preceding, the HI factor is estimated at stand level and throughout the entire cycle, and it therefore depends on the productivity of the stand and the site index. Thus the higher the site index is, the higher the amount of timber produced per area in the same period, which also depends on the species used. However, it is possible to compare management schemes with different site indices for the same species.

Regarding the case study used, harvesting was considered to be complete, as recommended in the evaluated management schemes; therefore, the HI corresponds to the average annual growth. However, in a real-world scenario, the volume extracted does not necessarily match this possibility, as interventions are not always perfectly implemented. In any case, high harvest intensity can have important ecological

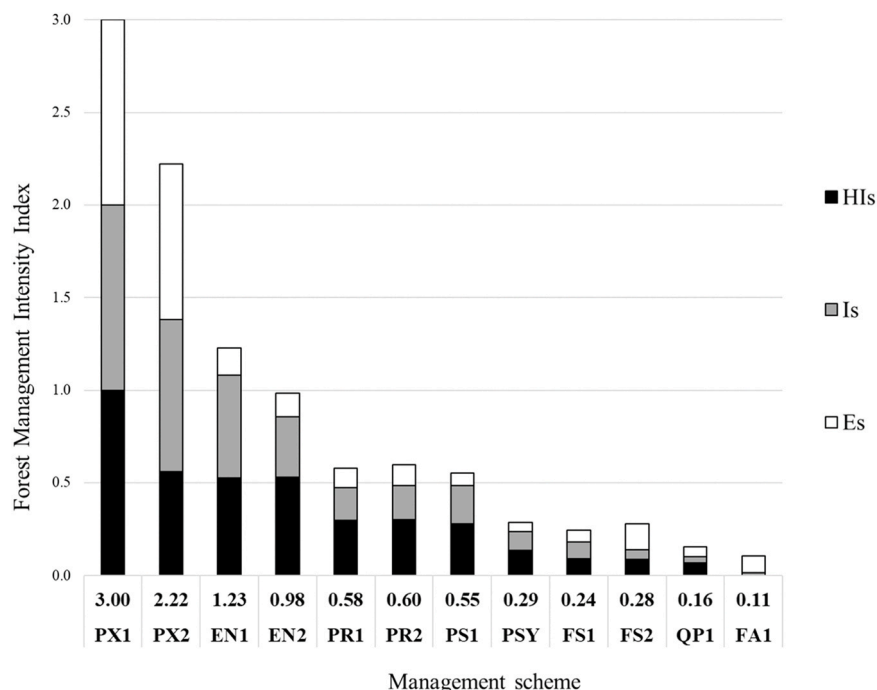


Fig. 4. Bar graph showing the values of the FMI and its components, harvest intensity (HIs), economic inputs (Is) and time spent (Es), for each management scheme.

implications. The rapid removal of biomass through short-term rotations may quickly deplete soil nutrients, whereas adhering to traditional, longer rotations is unlikely to result in nutrient depletion (Vadeboncoeur et al., 2014). This highlights the importance of HI as a key component of the FMI, linking management intensity not only to productivity but also to long-term ecosystem sustainability.

In the same way as HI, the I factor may or may not be applied in a forest system. In some cases, such as strict conservation, no intervention may be carried out at all, while in others, like recreational forests, interventions may occur without the manager being concerned about profitability. The I factor aligns with previous research, such as Solano et al. (2007), which highlights the usefulness of tools for comparing forest management schemes from an economic perspective. However, such studies often focus on profitability rather than solely on investment levels, as in the present case. The list of potential management interventions included in the index is intended to be comprehensive but tentative, and not all interventions need to be applied in every management scheme. While the current configuration does not distinguish between productive and non-productive interventions, the index can be adapted to make such a distinction if required, for example in applications related to forest certification. Other applications may seek to offset all costs or only those associated with less sustainable practices. Building on this, future applications could incorporate an ecological pressure index to analyse the relationship between FMI and intervention pressure, allowing the identification of activities with higher environmental impact.

The I factor reflects the use of management expenditures to assess the level of forest management, following the approach proposed by Arano and Munn (2006). Moreover, harvesting high-value sawn timber is not economically equivalent to extracting low-value wood biomass. Although the additional economic effort may be compensated by the higher market value of the product, it still exerts greater demands on the forest manager, as this index is specifically designed to reflect. For these reasons, revenues are not included in the calculation of I.

Two management schemes would be expected to produce the same volume of wood, even when felling is carried out at different stages of the cycle in one and in the other, it is carried out once, at the end of the rotation. However, in terms of effort, this requires the manager to carry out several administrative procedures that are reflected in the time investment, as well as contracting of the work, the supervision and prior monitoring of the stand to determine whether or not thinning is necessary. The same applies to log size, as the effort of harvesting small logs is not the same as that of harvesting large logs, for the same total volume. These are examples of why the E factor becomes vitally important when quantifying the effort dedicated by the forester. This more anthropocentric factor is not reflected in previous studies, but includes several essential aspects of forest management involved in the definition, such as administrative, legal, social, technical and scientific aspects (FAO, 2020). Future research should focus on developing more objective methodologies to refine the weighting process (Table 1), reducing subjectivity while still accounting for the variability across species, sites, administrative units, and national contexts. Moreover, the experience of forest managers could be considered by application of a correction factor that adjusts the value of the time dedicated based on the level of expertise and professional background. Advances in this direction could enhance the comparability and robustness of estimated time invested in management across different scenarios.

It should be noted that the FMI is based on a complete production cycle and therefore implicitly assumes relatively stable environmental conditions. While individual disturbances, such as pest outbreaks, extreme weather events or changes in species composition, are not explicitly considered, their effects could be incorporated by adjusting the management scheme. Changes in species composition would require defining a new management scheme too. This highlights an inherent limitation of the current FMI setup, while also suggesting a way to integrate environmental variability into future applications.

## 4.2. Case study

In the present case, only one value was calculated for each factor per management scheme and therefore a single FMI value was obtained. Within the same management scheme, the results can be complicated by the variability in the use of other price bases, initial plantation densities, site indices, discount rate used, topographic, edaphic and climatic conditions, as well as the specific geographical context. It is also important to highlight the need for reliable economic data on forest operations. In many countries, the availability and accuracy of such data can significantly influence the robustness and applicability of the index. Just as site quality for a given species can critically affect productivity and management decisions, economic variables can have a substantial impact on the FMI components. The absence of inconsistencies in these data may restrict the comparison of management schemes across regions.

The species used are similar to those used in the SMI in the study applied in Central European forests (Schall and Ammer, 2013). Thus, different management schemes that differ widely in factors such as productivity, inputs and dedication time were compared. The order between species obtained through the FMI is partly consistent with that obtained through the SMI: oak (*Q. robur* & *Q. petraea*) < European beech < Scots pine (Schall and Ammer, 2013). This agreement verifies the reflection of reality through the FMI, and thus its effectiveness in terms of comparing management schemes is corroborated.

Compared with the classification of Duncker et al. (2012) (see Table 2), the management schemes that could be classified as short-rotation forestry according to that system yielded the highest values of FMI (see PX1, PX2 and EN1 in Fig. 4), followed by lower values in the case of intensive even-aged forestry (see EN2, PR1, PR2, PS1 in Fig. 4), and then by medium-intensity schemes (combined objective forestry), represented in this study by PSY, FS1 and QP1. The lowest FMI value corresponded to stands characterized as unmanaged forest nature reserves, such as FA1. It is worth noting that in the case of close-to-nature forestry, classified as low intensity by these authors, the FMI value was slightly higher for FS2 (close-to-nature forestry) than for FS1 (combined objective forestry), due to the considerable time and effort the forester must invest to implement this management scheme, mainly showed in E. When comparing schemes with close-to-nature forestry (FS2) and strict conservation (FA1), the results indicate higher management values for FS2 across all factors. However, given the high variability in these management schemes depending on the context and the current importance of comparing closer-to-nature forestry and strict conservation schemes (Giadrossich and Scotti, 2025), applying the FMI to a wider variety of schemes of this type would be of interest.

Some management schemes prioritize intensive silvicultural interventions (e.g. PX1 with 36 interventions over 12 years), while others involve fewer stand entries (e.g., FS2 with 4 interventions over 10 years) (Table 3). Notably, FA1 stands out with a high number of recreational (60), educational (60) and social awareness (1) activities, along with legal aspects (4), research (2), surveillance (2), and inventory (2) actions, resulting in a total of 132 interventions over an average year, the highest among all schemes. The remarkably large number of recreational and educational activities is associated with regulation of access to these natural areas, as they experience almost continuous visitation for at least two months each year.

The highest FMI was obtained for poplar plantations aimed at biomass production (PX1), with the short rotation woody crop system (Fig. 4). The second most intensive according to the FMI is the cultivation of poplar for wood (PX2), due to the intensive care that the crop requires. However, these higher values are explained by their economic impact in the market, especially the forest system of poplar for timber production, exceeding 210.60 USD·m<sup>-3</sup> in some cases (CESEFOR, 2022). The eucalyptus stands are located in third and fourth place, with EN1 being slightly more intensive than EN2, which is explained by its shorter rotation and the number of interventions. The other systems then

appear in the following decreasing order according to the FMI values: PS1, PSY, FS2, FS1, QP1 and finally FA1. The lowest values of the index, were obtained for these systems, mainly due to the longer rotations and lower or non-existent (FA1) harvests. In summary, as expected, higher values of FMI were obtained in forest plantations (poplar, eucalyptus and pine) than in other systems. Nevertheless, although forest plantations represent less than 7 % of the total forest area in the world, they account for about 33 % of total roundwood production (FAO, 2022), providing essential raw material in sufficient quantity and quality to meet industry demands. This has been possible precisely because of the intensification of these systems.

A sum of standardized factors (Eq. 6) was used rather than a multiplicative approach to avoid having zero value in one factor (such as HI in conservation-oriented models) nullifying the influence of the others. Furthermore, it is possible that grouping these three factors into a single index might not make any sense, as combining economic effort with the manager's time effort, which also involves minimizing costs, could be counterproductive. However, these are indicators of aspects related to forest management that, taken separately, serve to characterize management schemes.

The values used to standardize the index (Eq. 6) were defined in this case study to test its application, but they can be readapted for use in other territories with different reference values. As previously noted, it is possible to obtain an index value greater than 3, which exceeds the initially proposed upper limit. However, this does not signify any errors in implementation, and it may simply reflect a more intensive management approach than proposed here as a case study. Accordingly, any of the three components can exceed unity. It is important to note that a high level of management is not necessarily negative. For instance, in a forest stand where fuel loads are managed intensively due to a high risk of wildfire, such management can be considered beneficial.

When comparing forest management schemes with similar FMI values, it is advisable to adjust the standardization scale ( $F_{Sk}$ ) to improve the resolution of the comparison. However, this also implies that the index becomes context dependent, limiting direct comparisons across different studies or regions unless a common standardization framework is used. Therefore, interpretation of FMI values must consider the reference context and scaling criteria applied, as changes in these parameters will affect the comparability and significance of the findings.

Among the three factors, the  $F_{IREF}$  is the most variable, as its value is strongly influenced by the assumed interest rate. Different rates can substantially alter the outcome and the overall FMI value. Adapting this parameter to the objectives and context of the analysis is thus recommended.

## 5. Conclusions

In conclusion, the FMI effectively quantified forest management intensity across management schemes with clearly distinct objectives (PX1, FS2, PA1), and even among those with very similar objectives (EN1 & PR1). Notably, multifunctional objectives (FS2) demand more management effort than traditional schemes (FS1) for the same species, while even old-growth forests demand some management. This reveals that zero intensity applies to abandoned stands. The values of the three factors proposed as management intensity indicators are directly proportional to the value of the index, which implies that crops requiring more care, higher inputs and greater productive capacity were associated with higher FMI values than crops with longer rotations or lower productive capacity. Likewise, each factor can also function as an independent index, allowing comparisons across them and facilitating a nuanced characterization of management schemes. While the comparison with previous studies reveals some consistency in the factors considered, the objectives and full applicability of the FMI had not been achieved before. Future research could explore the relationship between

FMI and ecosystem service degradation/contribution, evaluating the degree of contribution of these over the potential that it could provide us. This would enable evaluation of the opportunity cost in terms of ecosystem services that the choice of one management scheme or another entails.

## CRediT authorship contribution statement

**Yago Lestido-Cardama:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Roque Rodríguez-Soalleiro:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Carlos A. Gonzalez-Benecke:** Writing – review & editing, Supervision, Methodology. **Gabriel Tucker:** Writing – review & editing, Supervision. **Froilán Sevilla-Martínez:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Isabel Cañellas:** Writing – review & editing, Validation, Supervision. **Nerea Oliveira:** Writing – review & editing, Validation, Supervision. **Iciar Alberdi:** Writing – review & editing, Validation, Supervision. **Montes Pita Fernando:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition. **Juan Alberto Molina-Valero:** Writing – review & editing, Validation, Supervision, Methodology. **Santiago González-López:** Methodology, Data curation, Conceptualization. **Ulises Diéguez-Aranda:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **César Pérez-Cruzado:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

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## 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.

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## Annex

Table A1

Unit prices used to estimate the costs of each management scheme in Spain

Product	Unit cost	Unit	Product	Unit cost	Unit
Irrigation (Biomasa, 2007)	0.06 USD	m <sup>3</sup>	Digging holes (40x40x40 cm & >700 holes/ha) F01103	1.40 USD	Plant
Fertilization F02144	0.09 USD	Plant	Pruning (<3 m) F05037	1.87 USD	Plant
Initial fertilizer Mañente	0.09 USD	Plant	High pruning (4–8 m) F05052	1.94 USD	Plant
Plant from Tragsa	0.27 USD	Plant	Poplar 1 sap rod	2.03 USD	Plant
Eucalypt plant from Mañente	0.29 USD	Plant	Cost of harvesting (>30 cm) F06112	2.34 USD	Plant
Cost of harvesting (< 12 cm) F06104	0.41 USD	Plant	High pruning (<5.5 m) F05043	3.65 USD	Plant
Thinning (< 12 cm) F06104	0.41 USD	Plant	Poplar plantation F02128	5.97 USD	Plant
Thinning (12–20 cm & <750 plant/ha) F06108	0.43 USD	Plant	Deltametrin from BAYER	18.53 USD	ha
Low pruning (< 1,75 m) F05028	0.51 USD	Plant	Subsoiling F01176	81.81 USD	ha
Plantation bare-root plant F02083	0.60 USD	Plant	Tilling F09084	112.59 USD	ha
Thinning (12–20 cm & 750–1500 plants/ha) F06106	0.62 USD	Plant	Phytosanitary treatment (>500 plants/ha) F09119	176.29 USD	ha
Plantation containerized plant F02085	0.65 USD	Plant	Tree selection F06216	208.96 USD	ha
Thinning (12–20 cm & >1500 plants/ha) F06105	0.66 USD	Plant	Superficial tillage F01163	202.67 USD	ha
Thinning (20–30 cm & <750 plants/ha) F06111	0.64 USD	Plant	Mechanical control of competing vegetation F04080	309.67 USD	ha
Low pruning (1,8–3 m) F05049	0.75 USD	Plant	Milling cutting F09086	316.21 USD	ha
Fertilizer Mañente	0.78 USD	Plant	Eucalypt stump removal F09079	470.56 USD	ha
Plant replacement F03153	0.80 USD	Plant	Manual control of competing vegetation F04039	559.61 USD	ha
Beech/Pyrenean oak plant from Tragsa	0.82 USD	Plant	Poplar stump removal F09081	807.83 USD	ha
Cost of harvesting (20–30 cm & >750 plants/ha) F06109	1.01 USD	Plant	Herbicide treatment F09105	823.79 USD	ha
High pruning (3–4 m) F05050	1.16 USD	Plant	Master's degree holder with 5–10 years of experience O03002	32.20 USD	hour
Layout of CN–03, CN–05 and CN–08 type signals F11034	6.23 USD	Unit	Degree graduated with 1–3 years of experience O03009	22.08 USD	hour
Wooden milestone, fully installed F11023	65.42 USD	Unit	Off-road vehicle 71–85 HP M06010	5.30 USD	hour

## Data availability

Data will be made available on request.

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