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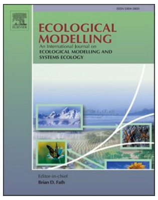

SIMANFOR cloud Decision Support System: Structure, content, and applications

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SUMMARY

Technological progress in the last decades has driven great advances in many fields of knowledge. A wide range of tools and services are now available and constantly evolving to handle vast amounts of available data as well as the increased complexity of real-world case studies and analytical alternatives. Most sectors have embraced new methodologies to provide solutions to their problems, and the forestry sector is no exception. Important steps have been taken to update the forestry sector and introduce new large-scale experimental designs, digital tools and more extensive forestry databases. However, assimilation of this progress by forest managers remains largely pending. The more specialized technical knowledge and computing skills required to use this new generation of tools constitutes a known barrier to uptake. In this work, we present the SIMANFOR cloud-based Decision Support System service for simulating forest management alternatives. Its evolution, internal structure and potential applications are described. A case study was developed to demonstrate simulator performance under diverse management scenarios and highlight the benefits of this tool for forest managers. SIMANFOR cloud services are free and can be accessed at www.simanfor.es.

1. Introduction

Modelling is a crucial complement to observational and experimental data in forest science. The term ‘model’ is often used to describe three separate concepts: platforms, models and parameterizations. To clarify, platforms are software tools for implementing models and their parameterizations. They are not associated with a particular model but can reflect a specific modelling approach: empirical (Pretzsch et al., 2002), process-based (Gracia et al., 2003, 1999), hybrid (Karki et al., 2023; Landsberg and Waring, 1997), etc. Models are abstractions of forest dynamics at different levels (tree, size-class, stand). These are represented by a set of equations, rules, and decisions that enable users to forecast forest dynamics. Local parameterizations are adaptations of models to specific locations and species compositions. The platforms generate representative tables, tree lists, and graphs for use by managers in operational forestry. These tools have been in use for some time and are evolving alongside forest management needs, to support decision-making processes.

Forest management involves a great variety and quantity of forest inventory data (experimental plots, LiDAR pointclouds, satellite data, etc.) and simulation data (growth, yield, climate change scenarios, etc.). The data can be raw or curated, derived from observation/experimentation or generated through simulations. It can be recorded in different ways (private or public, with or without embargo, linked open data, etc.) and stored locally or remotely in diverse proprietary or open formats. Data management can involve people in different locations; it may require workplace and remote access as well as specific knowledge to understand what is behind the data and arrive at the right conclusions. Typical aspects include data gathering, data storage, data curation, programming, and output generation and interpretation. Here, cloud computing can facilitate the storage and handling of massive amounts of data. Cloud computing has evolved to the point that we can find many examples of it in everyday life, and the forestry sector ought to harness its potential.

A wide variety of data is normally used to study forest dynamics. Permanent plots (PPs) allow researchers to study the evolution of forests over long periods. Some of the oldest plots that are still in use date back to the 19th century (Pretzsch, 2009). Experimental networks allow scientists to assess different effects on trees and stands and observe common behaviors among different location gradients (Pretzsch et al., 2019; Verheyen et al., 2016). For silviculture operations, thinning trials (Aldea et al., 2017) are a good example of how experimental networks seek to

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understand the effects of different harvest types. Provenance trials (Alía et al., 2009) evaluate how trees from various origins adapt to specific local conditions. Some countries have also developed National Forest Inventories (Tomppo et al., 2010), which provide large amounts of data for a variety of purposes.

Increasing concern about the effects of climate change on forest productivity and species distribution (Fernández-de-Una et al., 2015) has shifted the attention of the forestry sector to mixed forests, due to their higher resistance and resilience (Toïgo et al., 2015). A European triplet network was implemented to study and compare the single and combined effects of climate, and silviculture on pure and mixed stands of several species (Del Río et al., 2017; Poeydebat et al., 2020). Such experimental data is being used to address questions regarding productivity, competition, thinning effects, species proportion trends, etc. It allows for comparative analysis of pure and mixed stands, thinning intensities and site quality. However, to transfer this knowledge to forest owners and managers, tools must be implemented to simplify usability.

According to Schieman and Fiordo (1990), foresters are late adopters of information technology tools. Several initiatives have been launched to bridge the gap in recent decades. Among them are the System for Earth Observations, Data Access, Processing & Analysis for Land Monitoring (SEPAL) (FAO, 2022) and the Global Biodiversity Information Facility (GBIF) (GBIF.org, 2023), global-scale examples of database and data utilization resources. Data management tools such as basifoR (Bravo et al., 2024; 2022) and ForestExplorer (Vega-Gorgojo et al., 2022) offer solutions at a regional scale. Several simulator options are also available at regional and national levels. Simulators are digital tools that can run different silvicultural scenarios using forest-based input data and provide useful information for decision-making. They estimate forest metrics through models built from a combination of equations that are executed in the proper calculation order to estimate various forest metrics. The mathematical structure of the models can vary to accommodate different locations and/or species; or it can be maintained while the parameters are changed for each case study. Indeed, simulators can be adapted to specific locations and case studies (Pretzsch et al., 2015). They often implement models applied to mixed forests (Blanco et al., 2015) and estimation of natural disturbances (Seidl et al., 2011), providing new utilities for users. However, forest managers still encounter barriers when it comes to adopting these technologies. Easier user interface with the platform, low initial installation and input data requirements, and multiple application options are keys to expanding its use in supporting decision-making.

The main objective of this work is to show the opportunities that cloud-based simulations offer to the forestry community. Here, we present SIMANFOR, a cloud-based forest management simulation service and Decision Support System (DSS) that simulates a variety of forest management alternatives. We describe SIMANFOR's evolution from its original format (Bravo et al., 2012) to its current structure, the possibility of local or cloud-based use and the integration of the IBERO model (Bravo, 2005) as one of the many examples included in the platform. The IBERO case study is presented to illustrate the simulator's performance capabilities and highlight its benefits to forest managers.

2. SIMANFOR simulator

Although the idea behind SIMANFOR was conceived earlier, the first simulator version was originally developed in 2009 using the C# programming language in .NET. From the outset, SIMANFOR has been available online (Bravo et al., 2012). The original version had preloaded the IBERO model architecture (Bravo, 2005), designed to run single-tree growth models independent of distance. Over time, new parametrizations were included under the same model structure and the SILVES model architecture (Del Río et al., 2005; Del Río and Montero, 2011) was also implemented to run stand growth models. Additional ecosystem service modules linked to those models and their parametrizations were implemented, such as tree crown metrics (Lizarralde et al., 2004), tree biomass (Ruiz-Peinado et al., 2012, 2011), carbon content (Montero, 2005), and mushroom productivity (De La Parra Peral et al., 2017; Herrero et al., 2019).

In 2020, SIMANFOR was rewritten in the Python programming language (Van Rossum and Drake, 2009), which improved performance and added new functionalities. Equations dependent on tree distance (Uzquiano et al., 2021), climate-dependent growth models for fungi productivity in Mediterranean scrublands (Hernández-Rodríguez et al., 2015) and climate-dependent growth models for mixed stands (Rodríguez de Prado, 2022) were implemented in the new version. Case studies for ecosystem services production (Rodríguez de Prado et al., 2023; Vázquez-Veloso et al., 2024; 2022), integration of mixed-stand models (Bravo and Vázquez-Veloso, 2024; Rodríguez de Prado et al., 2023) and model evaluation and validation (Vázquez-Veloso et al., 2023) were also carried out with the SIMANFOR simulator.

The software architecture has a modular design to separate web interface from the simulator core. With this approach, the simulator can be used in the cloud, locally or via a high-performance computer when needed (Fig. 1).

In the SIMANFOR architecture, four software components run in Docker containers (Merkel, 2014), a technology widely used in modern software development to facilitate the design and deployment of modular components for use in different operating systems and cloud environments. The Docker containers run on virtual servers whereas the fifth component runs on a physical server.

The five components (Fig. 1), are:

- A MongoDB (Banker et al., 2016) database Docker container that stores all the application entities, such as forest inventories, silviculture scenarios, models and users.
- The backend Node.js + Express (Express JS, 2024; Node JS, 2024) container that manages the application's business logic at the core of the application. It communicates with the MongoDB database (using Javascript), the frontend (via Representational State Transfer Application Programming Interface (REST API)), and the simulator server (via the Secure Shell protocol (SSH)).
- The frontend is an Angular 9 (So, 2018) Docker container that receives user input, interacts with the backend via REST API and displays results and information to the user.
- The fourth component is an inverse Nginx proxy (Soni, 2016), which routes user requests to the frontend or backend according to the request and manages the application's web interactions.
- The simulator currently runs on traditional client-server architecture, receiving SSH commands from the backend and scheduling and monitoring jobs using SLURM (Yoo et al., 2003). The simulator is currently being modified and built as a Docker service and will run in its own container. The ability to execute simulations on the supercomputer at Caléndula HPC (SCAYLE, 2019) in the form of SLURM jobs will remain as an option for jobs with hundreds or thousands of plots and trees.

Despite the previous implementation changes, its conceptual structure as a simulator has remained the same. SIMANFOR is divided into three main modules that have remained constant since the first version: initialization, projection, and thinning (Fig. 2). To start the simulation, a forest inventory and a silviculture scenario summarizing the time projection and thinning activities must be provided as input data. Once a simulation starts, the input data is read by the system and the initialization process begins, in which missing values of the initial inventory are imputed. After that, the simulator performs each of the steps summarized in the silviculture scenario following the original order. When a time projection is selected, then equations concerning mortality, growth, and ingrowth are executed and tree and stand metrics are updated. When a thinning event is selected, thinning is applied according to the user thinning requirements for type (systematic, from above/below), intensity, and criteria (percentage of trees extracted

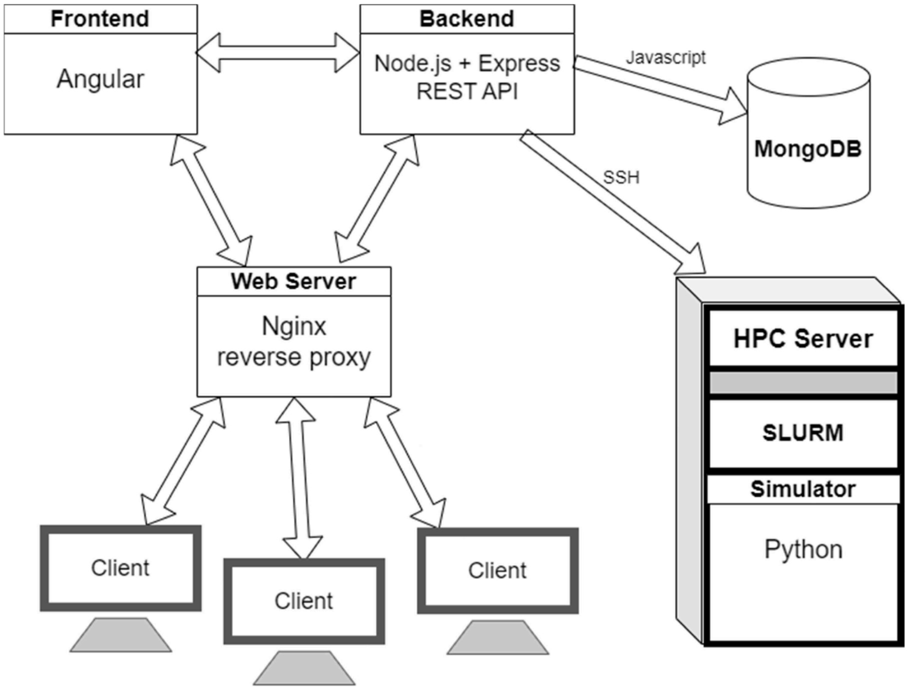

Fig. 1. SIMANFOR web interface and simulator architecture.

based on stand density, basal area, or volume). Finally, tree and stand metrics are updated. When all steps in the scenario have been executed, a unique file is generated for each plot. It includes a simulation summary with detailed tree and plot information for each step of the scenario.

3. SIMANFOR stand-alone simulator

The ability to run SIMANFOR locally is a developmental breakthrough. Developers can now access every model structure implemented by the simulator and add new parametrizations, implement new model structures, or include additional calculations such as ecosystem services. The local version also reduces the effort of testing and debugging new implementations, while ensuring the stability of cloud service updates.

External users interested in contributing with new models or parametrizations can do so by providing: (1) a model name and description; (2) the model structure and equations to be implemented; (3) model input requirements; (4) credits (authorship and citation); and (5) contact details. The information is summarized in a model description sheet available for users as a guide that developers can follow to program a new model or parametrization, according to the workflow shown in Fig. 3. In a nutshell, contributing users identify a model or parameterization not currently supported by the simulator and submit a request to the development team for its inclusion. With the request, they provide documentation for the model and a case study with data and expected output. Our developers implement it in the SIMANFOR stand-alone simulator, then interested users test the model and reporting bugs to the main developer. That debugging process continues until the computations are executed smoothly, prediction results are satisfactory, and a stable version of the model/parametrization is obtained. This can then be included in the SIMANFOR cloud and linked to documentation and test data.

When the number of plots included in the inventory reaches a certain level and/or the number of scenarios to simulate is very large, the computing requirements increase and become unfeasible to run on a personal computer. However, large-scale simulations can be launched in a high-performance computing (HPC) environment using the SIMANFOR local simulator. Users can contact the SIMANFOR technical team and arrange to run simulations on the iuFOR – University of Valladolid supercomputer. Simulations with even greater data and/or processing requirements can also be run at Caléndula HPC, the High-performance Computing Center of Castilla y León (SCAYLE, 2019). These centers have been used in prior published works developed with SIMANFOR (Rodríguez de Prado et al., 2023; Vázquez-Veloso et al., 2023b).

4. SIMANFOR cloud service

The SIMANFOR web interface is available in multiple languages (English, Spanish, French, Portuguese, Vietnamese, Galician, and Basque). Its help system contains several resources and user manuals in English and Spanish. User requirements include an internet connection, a web browser (the platform has been tested on Microsoft Edge, Google Chrome, Chromium, Mozilla Firefox, and Safari browsers) and a spreadsheet program for data management (Microsoft Excel, LibreOffice Calc or OpenOffice Calc).

Two different roles exist for the SIMANFOR cloud: administrator and user. Administrators are responsible for managing the system and authorizing privileges to other users. Administrators upload models already developed (as explained before), provide reliable documentation and test data, and ensure model accuracy and proper performance. Users can upload inventory data, check available models and parametrizations, select the parametrization that best fits the inventory data and simulate forest management scenarios. Users are responsible for the adequacy and accuracy of their management scenarios, the inventory data they use and the models they choose for their simulations.

The inventory data provided to the system is a critical point, as it must comply with the simulator's requirements. Available models have sample datasets to serve as a guide, and inventory templates are available to help reduce user effort. For field data collection, as an example, the TreeCollect Android (https://www.android.com/) app was developed to easily record tree information and upload it to the SIMANFOR cloud (Bravo et al., 2017). Current efforts are focused on the interface between ForestExplorer, an interactive tool for exploring the Spanish National Forestry Inventory (Vega-Gorgojo et al., 2022), and the SIMANFOR cloud. With easy intuitive steps, users will soon be able to prepare their SIMANFOR-ready inventory on ForestExplorer by selecting their areas of interest (province, plot, or polygon), applying filter

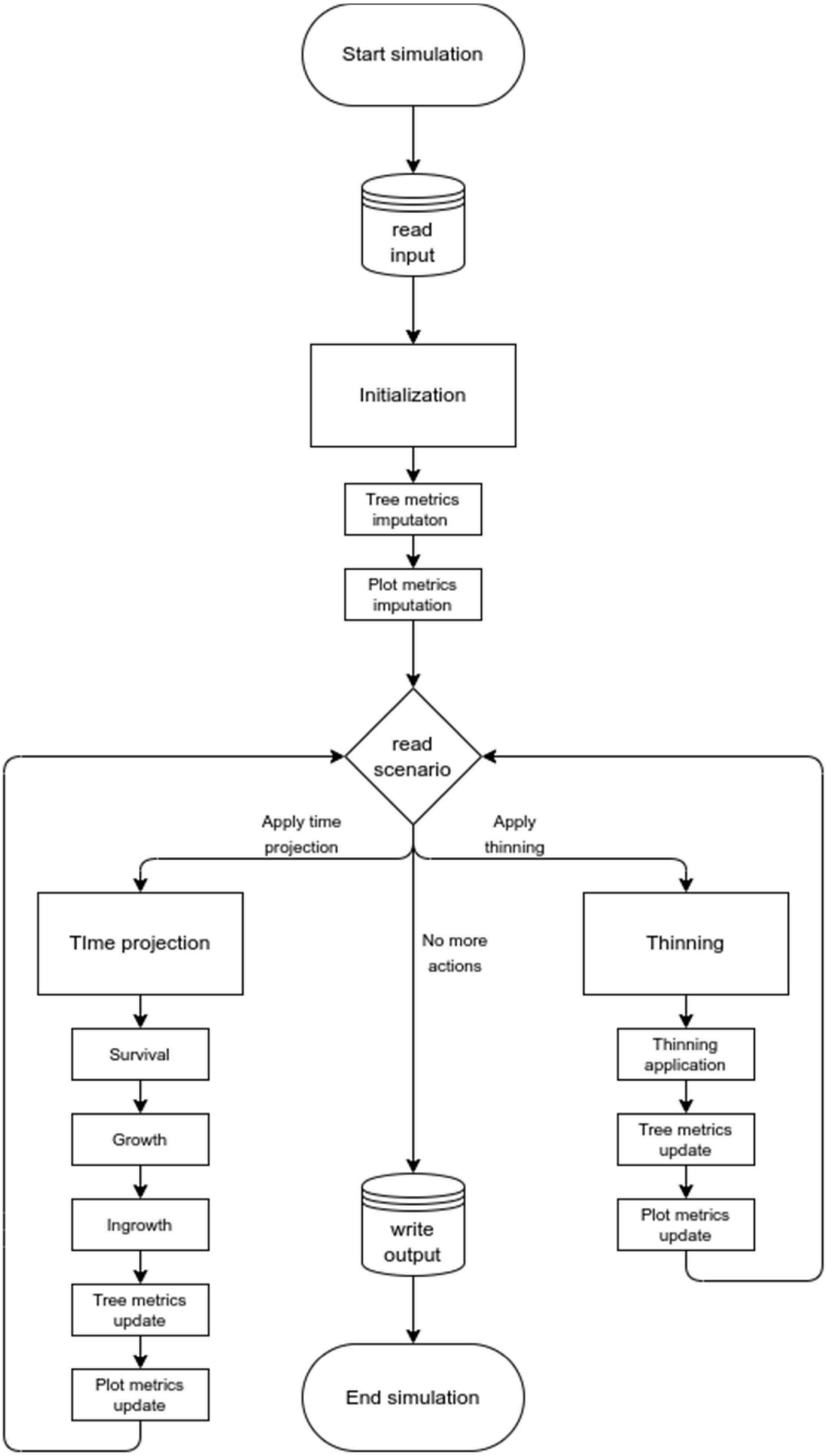

Fig. 2. SIMANFOR simulator structure.

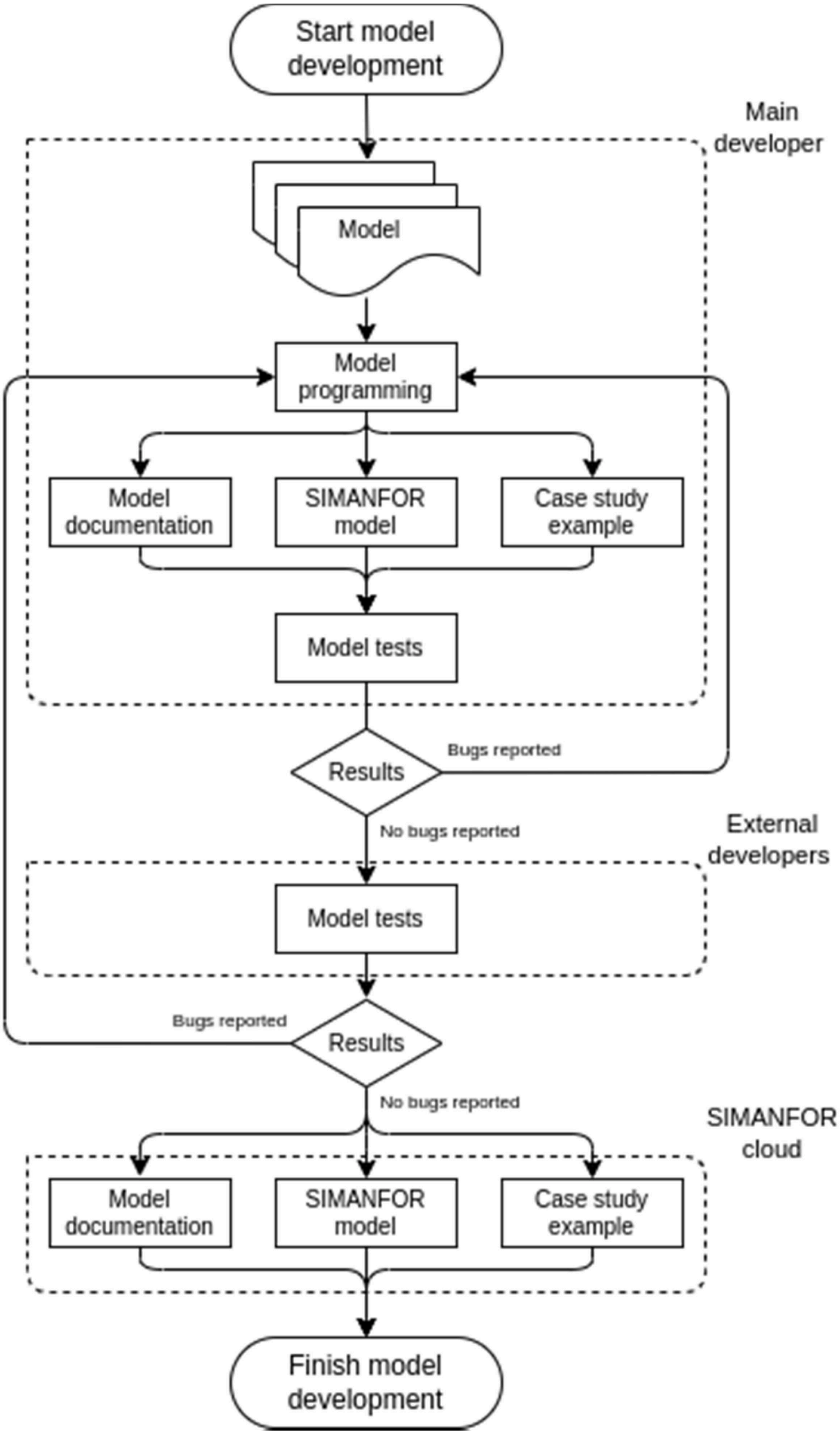

Fig. 3. Workflow for model/parametrization development on SIMANFOR, representing a case for including a new model. The same workflow applies to new parametrizations.

criteria (species, age…) and uploading the results to the SIMANFOR cloud.

Scenario management is another key aspect of the cloud service. Users can select their previously uploaded inventory data, the model and parametrization that better fits their requirements, and easily develop a silviculture scenario by generating time projections and thinning actions until the desired rotation period. An additional service is available via SMARTELO APP (Vázquez-Veloso et al., 2023a), an Android application that allows users to plan harvests directly in the field while exploring tree metrics. Forest managers can generate a silviculture plan and compare it on the website with alternatives generated by themselves or others. Both the inventory and the details of the thinned trees are sent to the SIMANFOR website, so users can initiate alternative future silvicultural scenarios following initial selective thinning in the field.

The simulation results are obtained after running each scenario. An Excel file is generated for each plot and scenario simulated, as the inventory data can include several plots. Each Excel file includes a yield table as a summary of the scenario; a stand sheet, where all the variables are calculated for each scenario step; tree sheets (one sheet per step) with updated information for each tree; a description sheet, where information about the model is provided; and a metadata sheet, where all the variables shown in the file are explained. A new functionality is currently being developed that will allow users to visualize their results as dynamic graphs developed with the Shiny R library (Chang et al., 2015). This facilitates easy graphic exploration of results and comparison with results from other silviculture actions.

Finally, documentation has been developed for each aspect of the simulator, to guide and support SIMANFOR cloud users. Manuals, test datasets, model descriptions, output examples and explanatory videos are available at: https://github.com/simanfor (SIMANFOR, 2022).

5. SIMANFOR applications

SIMANFOR is being used in three main areas: education, research, and forest management.

5.1. Education

SIMANFOR is an incredibly versatile educational tool for forestry students, forest managers and forest owners. With a range of usability options, it allows users to explore the effects of silviculture, climate, species mixtures, and other scenarios. SIMANFOR simulation output makes it possible to assess numerous ecosystem services and test strategies related to wood and non-wood resource production, allometries, species diversity and mixed-stand proportions (Rodríguez de Prado et al., 2023; Vázquez-Veloso et al., 2024). Overall, SIMANFOR provides an immersive experience to help users find the best silvicultural strategy and bolster their knowledge about forest modelling. The new, user-friendly cloud interface provides a better user experience, while associated apps such as TreeCollect (Bravo et al., 2017) and SMARTELO APP (Vázquez-Veloso et al., 2023a) enhance the simulator's usability and facilitate practical training opportunities in the field.

5.2. Research

SIMANFOR was born in a scientific environment and has been a valuable research tool in many areas since its creation. It offers practical support for understanding tree- and stand-level forest dynamics, enabling direct comparisons of productivity, climate, and silviculture scenarios. SIMANFOR is especially helpful for studying mixed forests and mixtures that have not yet been included in experimental trials. Its simulations can also provide initial insights about stand dynamics when experimental data is lacking (Bravo and Vázquez-Veloso, 2024). SIMANFOR can generate comprehensive growth and yield data for wood and non-wood resources, such as fungi (De La Parra Peral et al., 2017) and pine nut production (Vázquez-Veloso et al., 2022) in different scenarios, thus furthering study of the dynamics involved. Other research efforts have explored carbon content in relation to diverse silvicultural practices (Martín Ariza et al., 2017) or in mixed stands under varying climate scenarios (Rodríguez de Prado et al., 2023). Pioneering steps have already been taken to develop methodologies for model evaluation and validation (Vázquez-Veloso et al., 2023). Future research lines will integrate LiDAR metrics and models to expand user and research capabilities.

5.3. Forest management

As a simulator, SIMANFOR excels in its applicability to forest management, equipping and empowering users with a wide variety of silvicultural alternatives for assessment and comparison. Whether at tree, size-class, or stand level, SIMANFOR can simulate growth and yield for diverse temporal scopes. It facilitates static yield simulations along with extensive management plans spanning over a century, and supports decision-making by enabling users to assess a range of alternatives. Unlike earlier models that were primarily designed for pure stands, SIMANFOR includes mixed models that open new possibilities for exploring management strategies in scenarios of limited management experience, heightened complexity, and altered forest dynamics (Pretzsch and Schütz, 2014). To illustrate these capabilities, a case study is presented in the following sections. It describes how the IBERO model was integrated into SIMANFOR, and studies stand evolution under different management scenarios.

6. IBERO model integration

IBERO is an individual-tree growth model independent of distance developed by Bravo (2005). It was originally parametrized for *Pinus pinaster mesogeensis* and *Pinus sylvestris* even-aged pure stands. IBERO facilitates five-year projections (longer projections can be made with successive five-year projections) and incorporates different modules that are easily integrated into a SIMANFOR workflow (Fig. 4; see also Bravo (2005) for details).

Once a simulation starts and data is loaded, the initialization process begins. Here, the parametrization that best fits each plot included in the inventory is selected (for example, *Pinus pinaster* and *Pinus sylvestris* have different parametrizations). Productivity, driven by Site Index data (Bravo and Montero, 2001; Bravo-Oviedo et al., 2004), is calculated and does not vary during the entire simulation for each plot. Tree metrics are then calculated and default metrics such as basal area or bal (Wykoff et al., 1982) are imputed where information is missing. Species-specific metrics such as tree height (H/D), crown and volume (Lizarralde, 2008), merchantable wood volumes (Rodríguez, 2009), biomass (Ruiz-Peinado et al., 2012, 2011), carbon content (Castaño-Santamaría and Bravo, 2012; Montero, 2005), and mushroom productivity (Herrero et al., 2019; Sánchez-González et al., 2019) are also calculated. After that, common plot metrics like stand density and dominant height, along with metrics derived from the previous tree calculations such as stand volume and biomass, are imputed in the plot inventory.

Once initialization has finished, the simulator iterates the steps in the scenario and executes each one in the order provided. If the next step is a projection, then the survival (Bravo-Oviedo et al., 2006), growth (Lizarralde, 2008), and ingrowth (Bravo et al., 2008) modules are activated to calculate tree survival probability (Ps), diameter and height increment (DBHi and Hi), ingrowth probability (Pi), and basal area, all of which are then incorporated to the respective stand (BAi). Tree and plot metrics are then updated using the same equations. If the next step of the simulation is thinning, then the thinning module is activated according to user instructions. Tree and stand metrics are then updated as before.

Once the scenario has finished, the output is written to a file, along with the information pertaining to the model and the parametrization used to perform the simulation.

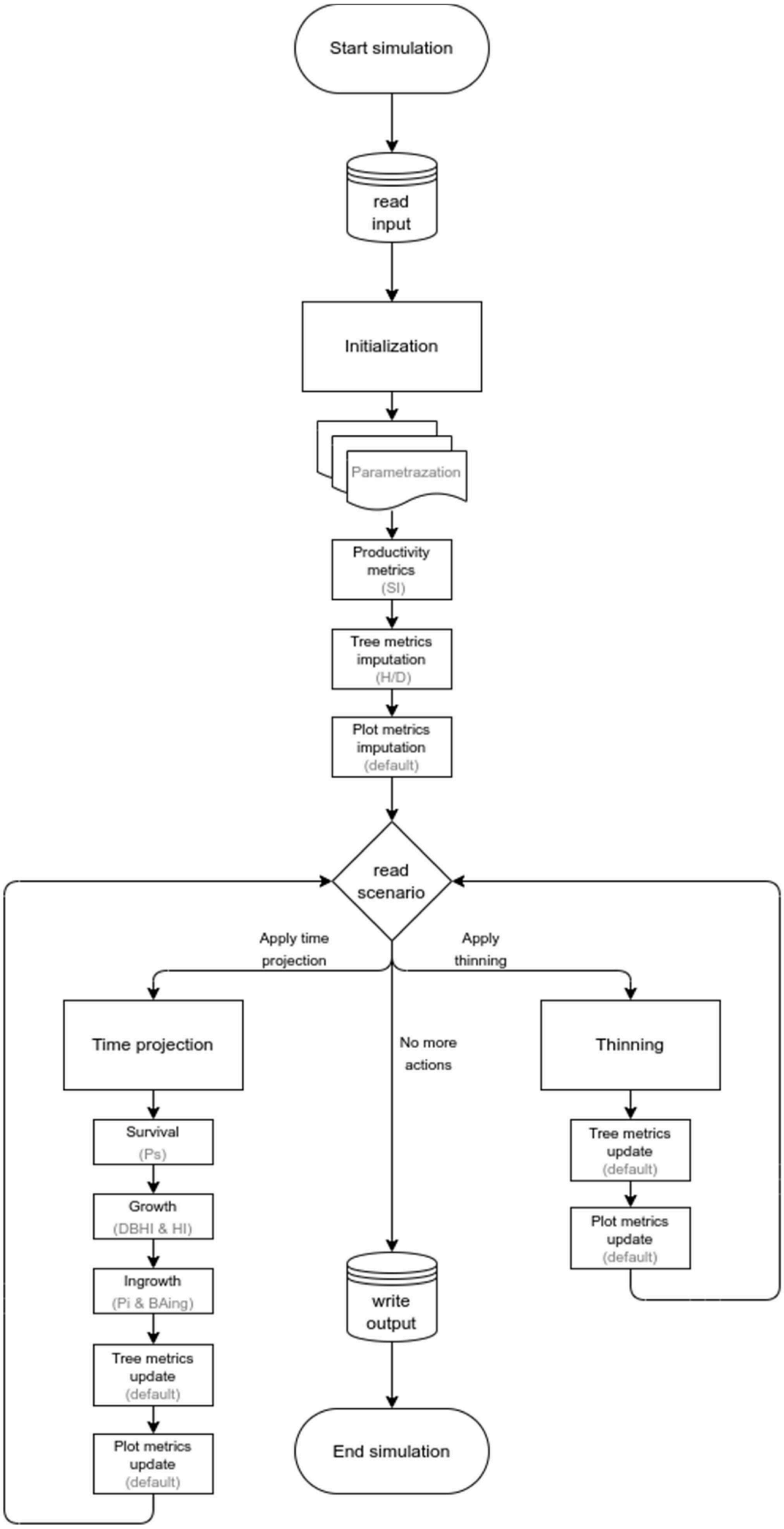

Fig. 4. Integration of the IBERO model structure into the SIMANFOR simulator. Grey font refers to specific components of the IBERO model that are explained in the text.

7. Case study

To illustrate how the SIMANFOR simulator performs, a silvicultural simulation was run using inventory data, the IBERO-PT model (IBERO model parametrization for *Pinus pinaster*), and the SIMANFOR cloud service.

7.1. Data

Initial data comes from five permanent *Pinus pinaster* plots located in the Southern Iberian Range (Spain). The plots were established in 2003 (see Table 1) and remeasured in 2008 and 2013.

7.2. Silviculture scenarios

Four silvicultural scenarios were defined by combining thinning type (from below or from above), and thinning rotation (every 10 or every 15 years). A control (no thinning) simulation was also performed to benchmark the results. In all cases, thinning intensity was set to 25% reduction in basal area. The projection time span for the stand was from the initial plot age to 81–83 years old, depending on the initial stand age. A summary is shown in Table 2, and more detailed information about each silvicultural scenario is available in Appendix A.

7.3. Results

The results of the main stand metrics are shown in Fig. 5. Both density (N) and basal area (G) show higher values when no silviculture is applied to the stand, while dominant height (Ho) as the quadratic mean diameter (dg) for scenarios 1 and 2 in which thinning from above is applied, is lower at the end of the simulation. Significant differences based on thinning criteria are also noticeable. While scenarios 1 and 2 (thinning from below) show higher dg values from the outset due to the removal of smaller trees, Ho was consistently higher during the simulation until 10 years ago, when it was surpassed by Scenario 3 (thinning from above every 10 years). Stand density was higher during the entire simulation in scenarios 3 and 4 (thinning from above) because the thinning objective of 25% of G is easily reached when bigger trees are removed. G is also consistently higher in those scenarios, though not compared to the reference Scenario 0.

The time between thinnings also significantly affected the outcomes. N presents lower values when thinning from below is carried out every 10 years (Scenario 1) compared to 15 years (Scenario 2), as a more intense extraction regime is being applied. However, the opposite behavior appears when comparing thinning from above. Higher N values are observed in Scenario 3, where thinning is performed every 10 years. Ho clearly presents higher values when thinning is performed every 10 years with both thinning types, which is likely related to the higher competition between remaining individuals. Differences in dg values are also significant when thinning is applied from below (scenarios 1 and 2) but show no discernable differences when applied from above (scenarios 3 and 4). Differences in G are not remarkable among any of the thinning scenarios.

To accompany these results, yield tables are available in Appendix B and complementary graphs for volume, biomass, and carbon content are available in Appendix C. The original results contained extensive tree- and stand-level metrics data, which can be found in the complementary data attached to this article.

Table 1
Summary of the inventory data. N is the stand density; dg is the quadratic mean diameter; G is the stand basal area; Ho is the stand dominant height; and SI is the Site Index at 80 years old.

Plot ID	Age (years)	N (trees/ha)	dg (cm)	G (m^2/ha)	Ho (m)	SI (m)
2,642,306	26	1510	15.1	27.2	10.8	22.1
2,644,107	29	2451	10.7	21.9	6.5	15.3
2,642,105	32	509	26.9	28.9	13.2	22.6
2,642,108	32	912	20.2	29.3	10.9	19.9
2,619,104	33	1252	13.7	18.4	8.0	16.1

Table 2
Summary of the scenarios simulated for specific thinning types and rotations. Thinning intensity remained fixed at 25% in basal area for all interventions.

Scenario code	Thinning type	Thinning rotation
0	None	None
1	from below	10 years
2	from below	15 years
3	from above	10 years
4	from above	15 years

8. Discussion

The IBERO case study illustrates SIMANFOR's potential for simulating and comparing forest management alternatives. Although only common stand variables were considered and compared, SIMANFOR generated a very large number of metrics at both tree and stand level. This demonstrates its capabilities for responding to a variety of requests, including more complex ones. Additionally, the separation between the simulator and the cloud service provides greater flexibility for the development of new functionalities and the inclusion of more metrics. The SIMANFOR technical team handles new implementations that users may request.

While IBERO was the first model structure integrated into SIMANFOR, new models with different structures have since been implemented. In cases where only stand information is available and tree data is missing, stand models can be applied on the platform. When the aim is to manage mixed forests or simulate the effects of various climate scenarios, specific models are available on the platform to support these situations (implementation is described in Bravo and Vázquez-Veloso (2024)). The mixed-forest model structure includes parametrizations for the 29 most extensively occurring two-species combinations in Spain and makes it possible for users to compare silviculture scenarios and their effects under future climate conditions. A case study comparing carbon sequestration in four *Pinus sylvestris* mixed stands is available in Rodríguez de Prado et al. (2023). Thus, the possibility of implementing new models, as the CAPSIS simulator does (Dufour-Kowalski et al., 2012), gives SIMANFOR an advantage over FVS (Crookston and Dixon, 2005) and similar alternatives. SIMANFOR's capacity to integrate parameterizations for different species and locations, or even different countries like Spain and Mexico, further enhance the usability of this simulator.

As a freely accessible tool, SIMANFOR enables forest managers and forest scientists to implement, test and run growth and yield models. However, throughout the SIMANFOR development process, certain barriers have been apparent: For a start, operational foresters are unfamiliar with cloud computing and therefore reluctant to apply this technology. SIMANFOR is very flexible, which some users may perceive as overly complicated. Also, the DSS relies on the convergence of good models, good data and good simulations. Finally, the time and effort required to understand how SIMANFOR works may be higher than initially expected. Developers and users should keep these barriers in mind when designing or adopting cloud-based DSS or facilitating the use of this technology in operational forestry. To overcome these obstacles, we are working to: keep the SIMANFOR cloud experience as simple and user-oriented as possible; develop ties with the forestry community (we are developing operational yield tables to engage them); keep the cloud interface clear and simple; provide adequate help and support for local problems along with accurate information for public discussion. Though time constraints and economic barriers tend to hinder such actions, we believe them to be the most influential activities for encouraging the adoption of cutting-edge technology. For example, the user interface reduces the effort required to access and implement SIMANFOR (see also Crookston and Dison, 2005; Dufor-Kowalski et al., 2012). Simplicity and cloud access that eliminates installation requirements give SIMANFOR an edge over alternatives without user interface, such as the SIMO

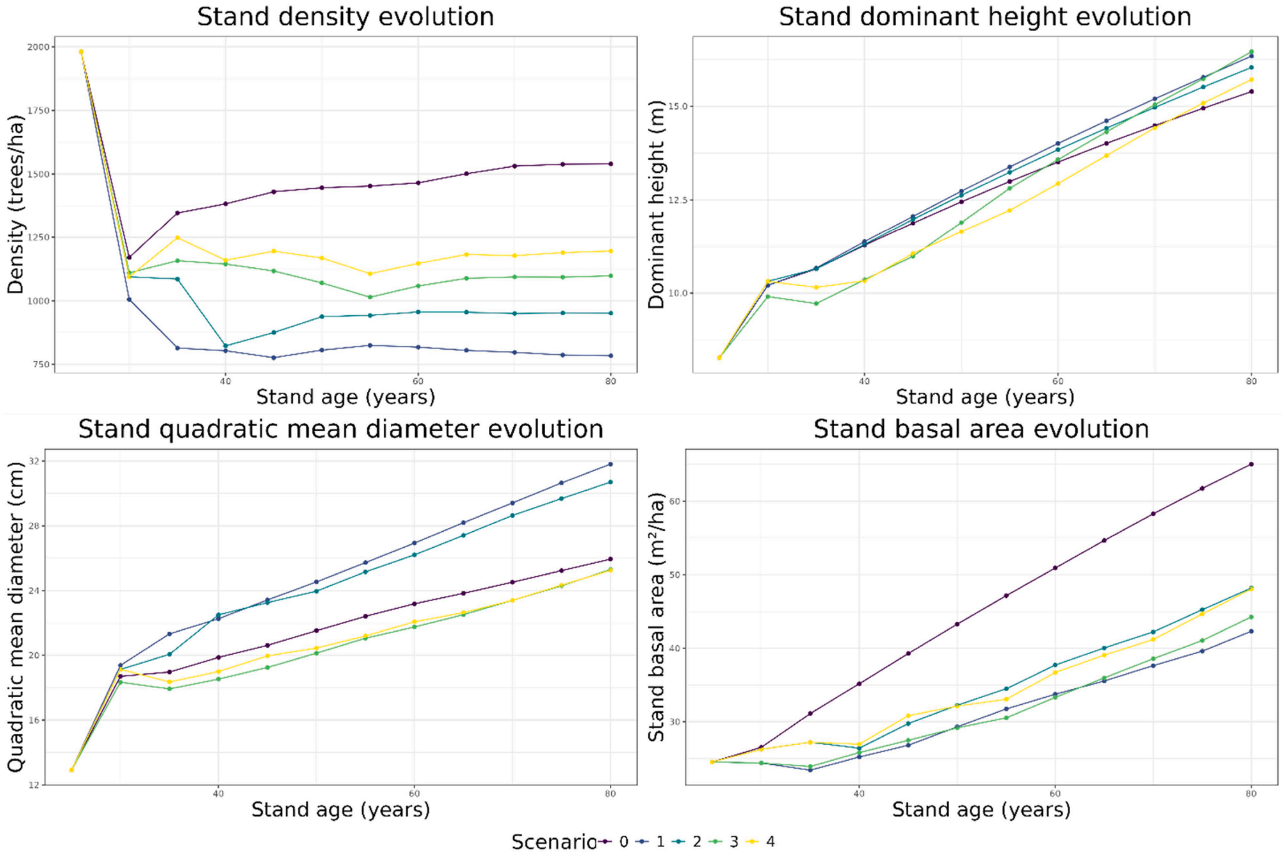

Fig. 5. Graph compilation with results of the main stand metrics. The evolution of stand density (top-left), dominant height (top-right), quadratic mean diameter (bottom-left) and basal area (bottom-right) are shown with the averaged results for the 5 plots studied. Each scenario is represented by one color, as shown in the legend. The peak that appears at under 30 years in all the graphs results from the different stand initial ages, as stand results are averaged and no initial information is available in some cases.

simulator (Rasinmäki et al., 2009), R libraries or SiTree (Antón-Fernández and Astrup, 2022), which require programming skills or allometric knowledge (Frank et al., 2023).

Additional services that are already integrated into the simulator to overcome usability barriers include low computational requirements, on-demand access to HPC services, facilities to develop and manage forest inventories, the possibility of simulating multi-plot data sets simultaneously and tailoring the output to specific requirements, and the ability to include and test new models, parametrizations or metrics as needed for the end users. The 'internet of things' (IoT) can also play a crucial role in collecting forest data (Bo et al., 2011) for process-based modelling. Detailed data can be integrated into spatially explicit growth models to improve predictions at various time and spatial levels. Further work is needed to implement IoT outcomes as part of the SIMANFOR platform.

Forest monitoring and forecasting through cloud computing platforms enhances the performance of forest scientists and managers through tools such as Google Earth Engine (GEE) or SIMANFOR by accelerating data collection, data processing, knowledge generation and operational applications. To further integrate cloud-based computing into forestry, Han et al. (2023) has proposed a distributed storage model to help managers evaluate forest processes that impact carbon sequestration.

Finally, while many resources have been developed, new projects are underway to provide a better experience and more tools for SIMANFOR users. We foresee that users will soon be able to view simulation results in a graphically pleasing and illustrative manner using Shiny R software (Chang et al., 2015). Similarly, we are working to develop more intuitive creation and editing of silviculture scenarios, while also packaging the stand-alone simulator into a Docker container microservice. From the user support side, the manuals are constantly being updated and introductory videos will reduce the time spent learning to use the simulator. From the technical side, future updates will include new metrics that provide more details about user silviculture, along with new models and parametrizations for different species and locations. We are also working towards the implementation of LiDAR metrics and models to expand usability. More ambitious works in the pipeline include the integration of ForestExplorer as described in Giménez-García et al. (2024), which will allow users to visually select their plots and create inventories that can be uploaded directly to the SIMANFOR cloud. We also hope to introduce a low-code application add-on for easier inclusion of a new model or parameterization of an existing one, along with customizable interface features that allow users to personalize the look and feel of the application.

9. Conclusion

This paper presents the SIMANFOR forest management simulator, its evolution and the structure of the simulator and cloud service, which are freely available at www.simanfor.es. SIMANFOR cloud is a support tool for forest management that provides a large amount of information with little user effort through a simple, user-friendly interface. Its applicability has been amply demonstrated in education, research and forest management. SIMANFOR is under continuous development and new features are constantly being incorporated. Furthermore, SIMANFOR can integrate models and parameterizations from different ecosystems around the world. Its simulations are supported by a server that can be scaled up to accommodate future demands.

Abbreviations

dg: Stand mean quadratic diameter (cm)
DSS: Decision Support System
G: Stand basal area (m2/ha)
Ho: Stand dominant height (m)
HPC: High Performance Computer iuFOR: University Instituto of Research in Sustainable Forest Management
N: stand density (trees/ha)

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CRediT authorship contribution statement

F. Bravo: Writing – original draft, Supervision, Software, Resources, Project administration, Funding acquisition, Conceptualization. **C. Ordóñez:** Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Formal analysis, Data curation. **A. Vázquez-Veloso:** Writing – review & editing, Writing – original draft, Visualization, Software, Formal analysis, Data curation. **S. Michalakopoulos:** Writing – review & editing, Writing – original draft, Software.

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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This new version has been programmed in cooperation with Sngular (https://www.sngular.com/), based on the authors' design, It is currently maintained and updated by the iuFOR Research Institute at the University of Valladolid (Spain).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2024.110912.

Data availability

Original data, code, figures and all the referenced used on this manuscript are available at https://zenodo.org/doi/10.5281/zenodo.12772484

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