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Multisilva: A Web-Based Decision Support System to Assess and Simulate the Provision of Forest Ecosystem Services at the Property Level

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Abstract: Forests provide a variety of ecosystem services (ESs) that contribute to a society's wellbeing. ES provision depends on the structure and evolution of forest ecosystems and is influenced by forest management. Society's increasing need for ESs requires these complex ecological dynamics to be understood and integrated in forest management and planning. We present the decision support system (DSS) Multisilva for multifunctional forest management. The Multisilva DSS is a web-based application that comprises two tools: the Mapping tool and the Simulation tool. The first tool provides spatial statistics and maps of the current provision of ESs at the forest property level. The Simulation tool compares two alternative, user-defined management scenarios over time and returns the biophysical estimations of ESs and the economic costs for each alternative. Multisilva is calibrated for Luxembourg, though it can be adapted for other temperate forest regions.

Keywords: ecosystem services; forest management; decision support system; forest; silviculture; simulation; mapping

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1. Introduction

In the last few decades, researchers and policy makers have addressed the importance of ecosystem services (ESs), i.e., the benefits that people obtain from nature [1], for society's wellbeing [2–5]. Forests provide a large variety of ESs such as wood and timber, carbon sequestration, air and water purification, habitats for protected species, and recreational opportunities [6]. ES provision depends on the structure and evolution of forest ecosystems, which may be influenced by forest management. The recent literature shows that an increase in the supply of multiple forest ESs can be guaranteed if sustainability practices of multifunctional forest management are applied [7–9], which cannot be limited to simplified assessment frameworks. Despite the global upsurge in tools and methods to support sustainable forest management [10–12], society's increasing need for ESs calls for a more sophisticated approach to forest management and planning that integrates ecological and socio-economic dynamics [13,14]. Methods and tools that exist to guide forest land managers and owners towards the achievement of best practices in multifunctional forest management fall under the umbrella of sustainable forest management certification schemes and rely on international protocols of forest ecosystem services and product supply-chain standards such as those promoted by the FSC (https://fsc.org/en, accessed on 24 November 2024) and PEFC (https://www.pefc.org/ accessed on 24 November 2024). The adoption of certification protocols represents a meaningful solution for maintaining competitiveness while ensuring sustainable management practices for biodiversity protection and conservation [15,16]. Nevertheless, it remains unclear how the multifunctional role of forests in keeping or increasing the supply of ecosystem services is guaranteed through the adoption of certification schemes [17]. Moreover, there is no evidence of forest cover loss mitigation being associated with the expansion of certified forest areas [18].

Enhancing the provision of ecosystem services in forest management necessitates the implementation of targeted management actions. To support these actions, it is central to have verifiable impacts. To address this need, the FSC introduced a specific procedure in 2021 (a revision is ongoing and is expected in 2025) to certify the enhanced provision of five key ecosystem services: carbon sequestration, water purification, soil conservation, biodiversity preservation, and recreational opportunities [19]. These procedures employ a theory of change approach, outlining a series of interventions designed to achieve the desired benefits, supported by a comprehensive monitoring strategy. Importantly, these interventions are often funded by companies or philanthropic institutions seeking to enhance ecosystem service provision as part of their sustainability commitments. Third-party audits ensure the validation of interventions, the rigour of the methodologies used, the coherence of the monitoring processes, and the effectiveness of the final implementation. Designing these management interventions to support the FSC ES procedure or to simply integrate ES-specific actions into management plans can be a challenging and time-consuming task.

The main research objective of this paper is the development of a decision support system (DSS), called Multisilva, able to facilitate the implementation of ES-oriented forest management. Such computer-based support systems represent and process knowledge to allow the user to take decisions that will have a more profitable or appropriate effect [20,21]. A key aspect of such decision systems is defining the issues, or parameters, that indicate a better or worse effect.

A comparison of multifunctional forest DSSs was conducted through a review of tools listed on the Forest DSS Community of Practice (http://www.forestdss.org/CoP/ accessed on 24 November 2024), complemented by targeted research to identify additional relevant details and links. The tools were then assessed and scored across multiple dimensions, including temporal and spatial scales, ES inclusion, management support, spatial explicitness, access type, and geographic focus (see Supplementary Materials). A subset of tools with available descriptions or links was selected for detailed evaluation, forming the shortlist. This final comparison highlights the diverse capabilities of these tools, which vary in their ability to address ESs, provide management support, and cater to different geographic and operational contexts.

Several DSSs in the shortlist reveal key gaps in their capacity either to support multifunctional forest management or to align with the FSC ES procedure. Many tools analysed, such as ESC, OpTimber-LP, VDDT-Path, and GISCAME, lack the ability to estimate ESs, which limits their utility for evaluating and enhancing ES provision. Tools like iTree and Collect Earth focus narrowly on specific applications, such as urban tree species or land use, limiting their applications in forest management. While some tools, such as Sim4Tree and SORTIE-ND, provide spatial explicitness, their functionality is constrained to stand-level management or by the significant amount of data input needed. Furthermore, global tools like InVEST and Co$ting Nature lack integration for forest-specific ES modelling and management or require external mapping software, complicating their application for practical forest management. Several region-specific tools, including IPTIM and Forest Management Optimization, address only a subset of ESs (e.g., carbon and timber), leaving gaps in assessing trade-offs among multiple ESs.

These limitations underscore Multisilva's unique position to fill these gaps by providing Europe-wide applicability, explicit modelling of actions to enhance ESs, comprehensive ES indicators for trade-off analysis, and integrated spatial explicitness tailored to forest ecosystems. Multisilva's ability to support standardised methodologies across countries aligns closely with the FSC ecosystem service procedure, which requires robust and consistent frameworks for ES management and monitoring.

The basis of the system presented in this study is ecosystem services and how forest management can affect their provision. While this has also attracted the attention of other researchers [22,23], the novelty of our system is the focus on multifunctional forest management and ecosystem services by computing and comparing the provision of various ESs, as well as the economic outcome deriving from different alternative management scenarios. Furthermore, with our knowledge of European policy, silvicultural practices, and social context, the presented tool is especially suited to the European market.

2. Decision Support System

2.1. Ecosystem Services as the Focal Point

Understanding the current provisions and needs in terms of ESs is central to the design of multifunctional forest management. In Luxembourg, as in many European countries, public access to environmental data is granted by the Aarhus Convention [24], of which the EU and all its members are signatories. This may include spatial datasets that can offer direct information on ESs or can be used to build relevant ES indicators. However, accessing these datasets, data cleaning, harmonisation, and computing the ES indicators can be very time-consuming and resource-intensive [25]. For this reason, development of tools to clearly visualise ES parameters and indicators was a critical component of the presented DSS, to leverage the available ES data in a user-friendly and ergonomic way.

2.2. Multisilva: Design and Architecture

The Multisilva DSS was developed to support forest managers and practitioners to understand the local needs in terms of ES provisions, and how these could be enhanced by varying management practices. The tool was designed in collaboration with the expected users, such as forest managers and engineers, to be ergonomic and easy to use.

Multisilva comprises two tools, or core functions (Figure 1): the Mapping tool and the Simulation tool. The Mapping tool provides spatial statistics and maps of the current provision of ESs for a given forest property, supporting the user in identifying ES hotspots and designing the forest management to enhance the provision of ESs. The Simulation tool considers alternative forest management strategies. It computes the ecological dynamics of the forest property over time and simulates the impacts of a set of management actions. The Simulation tool can compare two alternative, user-defined management scenarios and returns the biophysical estimations of ESs, as well as the direct costs and the opportunity cost for each alternative.

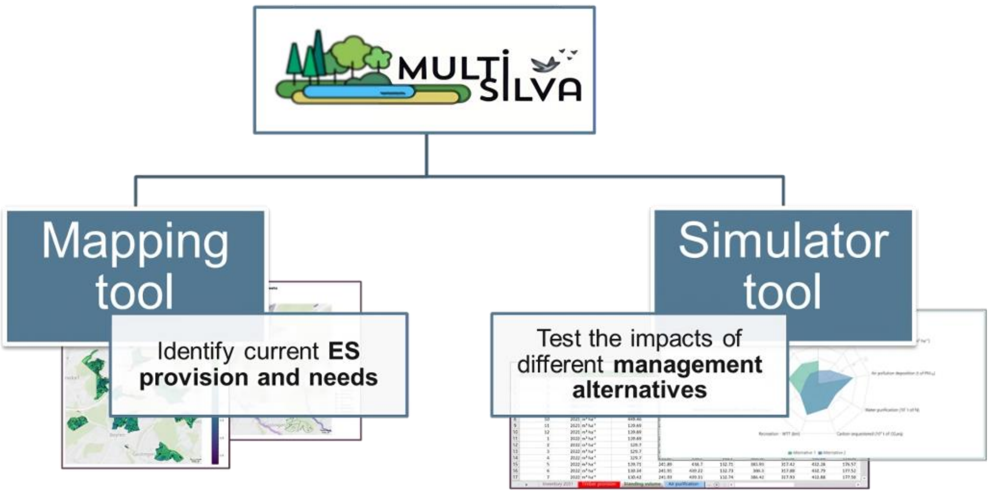

Figure 1. Multisilva decision support system structure.

The software system architecture is presented in Figure 2 and Table 1. The DSS is accessible as a web-based application, as illustrated in this demonstration video clip: www.youtube.com/watch?v=Hd3hN-vHi2c, (accessed 24 November 2024). A Keycloak instance grants access to the authorised users to pages providing the DSS functionalities to the user.

The web application is made with Nuxt using VuetifyJs components. Through this web application, the user can input the forest inventory data as well as the forest property map and download the template for the definition of management actions. These input data are then sent to the DSS backend, a REST API application made with Starlette in Python. This runs the main core functions of Multisilva.

The current version of the Multisilva DSS (v0.1.6) is currently customised for Luxembourg, capable of reading inputs formatted according to the Luxembourgish standards. With the Multisilva database covering the entire national territory, the system can be applied to any forest property in the country. The Multisilva DSS can, however, be adapted to other geographical contexts given appropriate adaptation of the software.

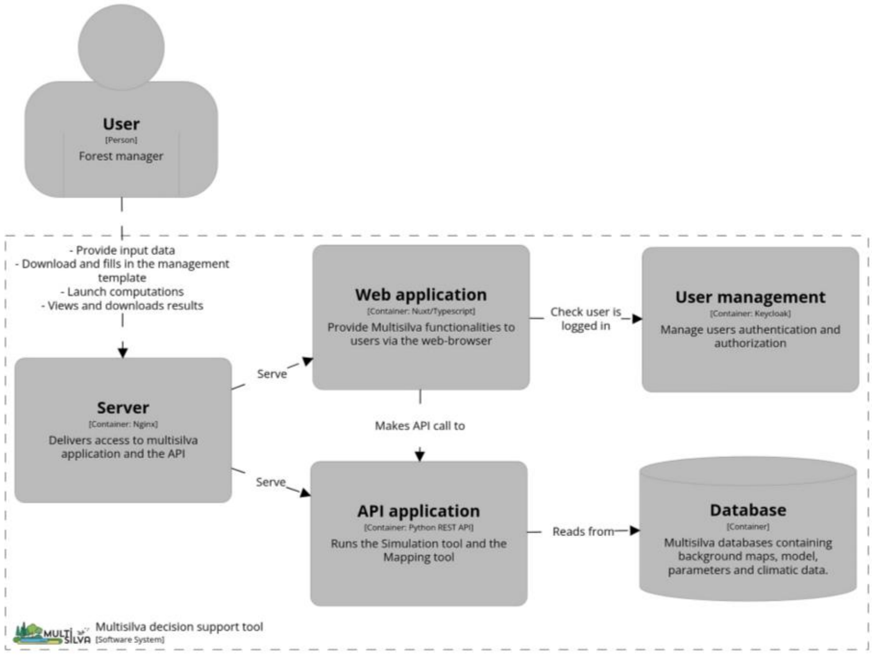

Figure 2. C4 system context diagram of the Multisilva software system.

Table 1. Principal components of the design and the technologies utilised.

Services	Goal	Technologies
Server	Delivers access to Multisilva application and the API	Nginx—version 1.25
Web application (version 0.1.6)	Provide Multisilva functionalities to users via the web-browser	Nuxt/Typescript
User management	Manage user authentication and authorization	Keycloak—version 24
API application (version 0.1.7)	Runs the Simulation tool and the Mapping tool	Python (version 3.11) REST API
Database	Multisilva databases containing background maps, model, parameters and climatic data.	Various file types

2.3. The Mapping Tool

The scope of the Mapping tool is to identify the ES needs and hotspots for the target property and its surroundings, and hence support the user in choosing the appropriate management actions, which could then be tested through the Simulation tool. The Mapping tool provides maps and statistics on seven indicators and proxies representing the current provision of cultural and regulating ecosystem services.

The tool is accessible via a user interface (Figure 3) from the web application. From the interface, the users can upload the zipped shapefile of the forest property (in the box "Shp loader"), providing the subdivision of the forest property in management units. The user interface also has an interactive map in which the forest property is automatically displayed once the zipped shapefile is loaded. Furthermore, there is a search function that helps the user to identify the location of specific management units within the property in the interactive map.

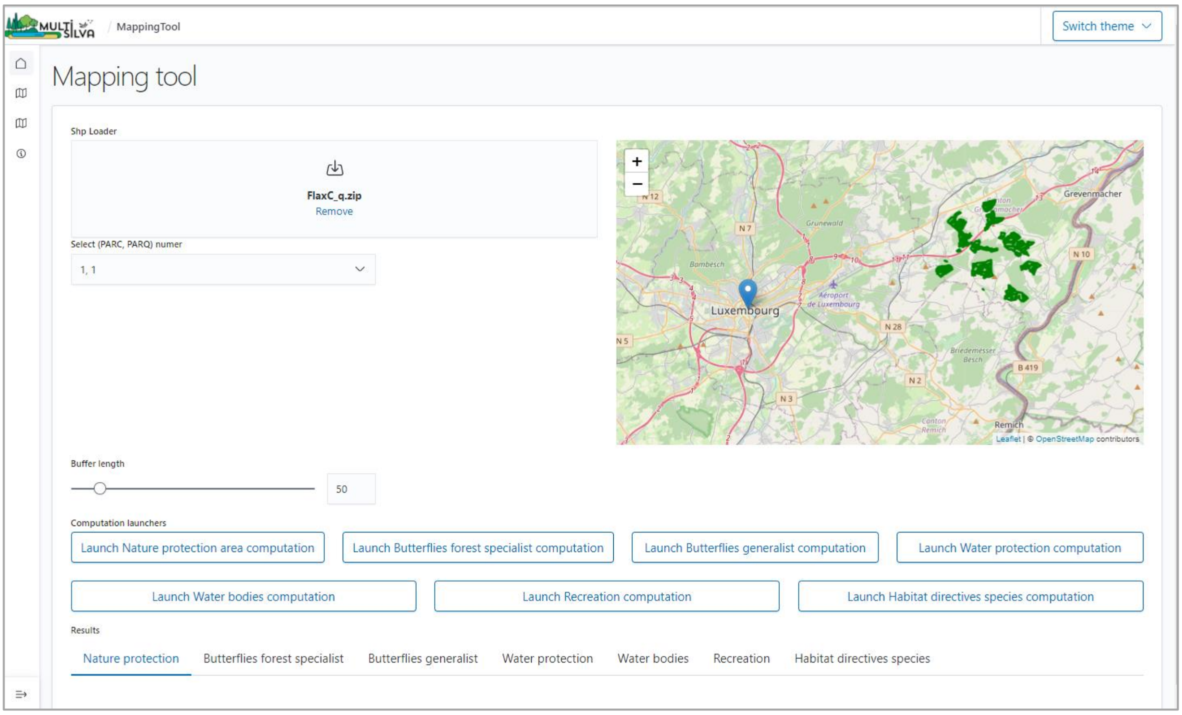

Figure 3. The user interface of the Mapping tool.

Once the zipped shapefile has been uploaded via the user interface, it is sent to the API server, in which a Python module (based the packages *geopandas* and *rasterio*) operates seven functions overlapping the shapefile with the ES indicator maps stored in the Multisilva database.

The seven functions are activated by the user from the user interface using the boxes in the "Computation launchers" section (Figure 3). Each function computes spatial statistics at management unit level for a set of regulating, cultural, and supporting ES indicators and proxies. An overview of the offered functions is presented below, with more details, including the methods and background data used to develop them, described extensively in Appendix A.

The first function is the *water protection computation*. This function overlaps each forest stand in the property with the water protection areas as defined by national regulations. Different levels of protection are present in Luxembourg (drinking-water protection zones, provisional drinking-water protection zones, and sanitary protection zones), and each corresponds to different management requirements requested by the national law. This function warns the user on legal management constraints that may have to be considered in the overlapping areas, but it can also provide important inputs for managing stands close to these hotspots.

The second function is also related to water-regulating ESs. The *water bodies computation* draws buffer areas around the main rivers, lakes, and creeks and provides the percentage of the management unit area overlapping with the buffer. The user can set the width of the buffer from the user interface (the pre-set value is 50 m). This function relies on the national shapefiles of the surface water bodies. The objective of this function is to identify riparian zones and areas to which forest management should be tailored (e.g., selection of species, residual removals to avoid nutrients runoffs, etc.).

The third function is called the *nature protection area computation*. This function overlaps each management unit of the property with different types of nature protection areas (e.g., Natura 2000 areas, national natural reserves, etc.) and provides the percentage of each management unit area intersecting the different types of nature protection areas. As for the "water protection computation" case, this function warns the user on legal management constraints and supports the identification of biodiversity hotspots.

The Mapping tool also offers three additional functions computing biodiversity indicators. First, the *butterflies forest specialist computation* computes the number and type of forest-specialist butterfly species that are potentially present in each management unit. Similarly, the *butterflies generalist computation* provides similar information for butterfly species that are found both in forests and open landscapes. Butterflies are one of the best indicators of biodiversity, and their monitoring records can be used to prioritise the types of land management and for environmental assessments of conservation strategies [26]. The third function computes the number and type of Habitat Directive [27] protected species that are potentially present in each forest stand. These three functions rely on the species distribution models (SDMs) computed by the Luxembourgish Ministry of Environment. An SDM aims to predict the presence records of a species with spatially explicit environmental variables (e.g., temperature, precipitation, topography, geology, and land use). Overall, mapping the predicted distribution of endangered species provides key information to support multifunctional forest management. By knowing the location in which certain species are more likely to be found, it is possible to identify stands in which specific forest management favouring this species can be applied. Such information can also help to identify potential management trade-offs with the conservation of other species or with other ESs. This function of the Mapping tool can be applied to other species of functional groups and in different countries, provided that SDMs are available.

The final function offers indicators concerning cultural ESs and specific outdoor recreation. The *recreation computation* command computes the average, maximum, and minimum score of the outdoor recreational attractiveness in accordance with two types of archetypical outdoor recreation user groups [28]: convenience recreationists and sportive recreationists. The former group reflects recreationists preferring an accessible and close-to-home landscape with a high level of attractiveness or scenic beauty, possibly with proximity to water with paths or trails. The sportive recreationists privilege landscapes allowing for outdoor sport recreation (running, Nordic walking, cycling, mountain biking, orienteering, etc.), possibly with marked tracks and good air quality. Following the framework of Komossa et al. [29], the recreation potential module in the Mapping tool assigns a score between 1 (low) and 5 (high), reflecting the potential of a specific area (in our case, a 10 m × 10 m pixel) for outdoor recreation of a specific user group. This recreation potential score is computed as the combination of landscape characteristics (e.g., vegetation structure, water proximity, air quality, and presence of marked tracks or paths) weighted by the value each user group assigns to them (data obtained from [29]). The pixels' scores are then averaged at the management unit level.

The results generated by the seven functions are then displayed in the user interface in tabular and map formats. The user can download the map tables displayed on the user interface in csv and jpeg formats. Maps are generated automatically with a title, legend, background topographic map, scale, and north arrow, ready to be used in reports and other media.

2.4. The Simulation Tool

The Simulation tool compares the ESs provided by alternative forest management paradigms for a specific forest property. The tool can compare two alternative, user-defined management scenarios and provides the biophysical estimations of ESs, the direct costs, and the opportunity cost for each alternative.

2.4.1. User Interface

The tool is accessible via a user interface (see Figure 4) where the user can upload the inputs required to run the simulation and set the simulation length (end year and end month). The inputs required to run a simulation are as follows: (i) a zipped shapefile of the forest property, (ii) an Excel file with the forest inventory, and (iii) the Excel files defining the management alternatives. Moreover, it is possible to upload a user-defined thinning schedule that overrides the standard schedules in the default settings.

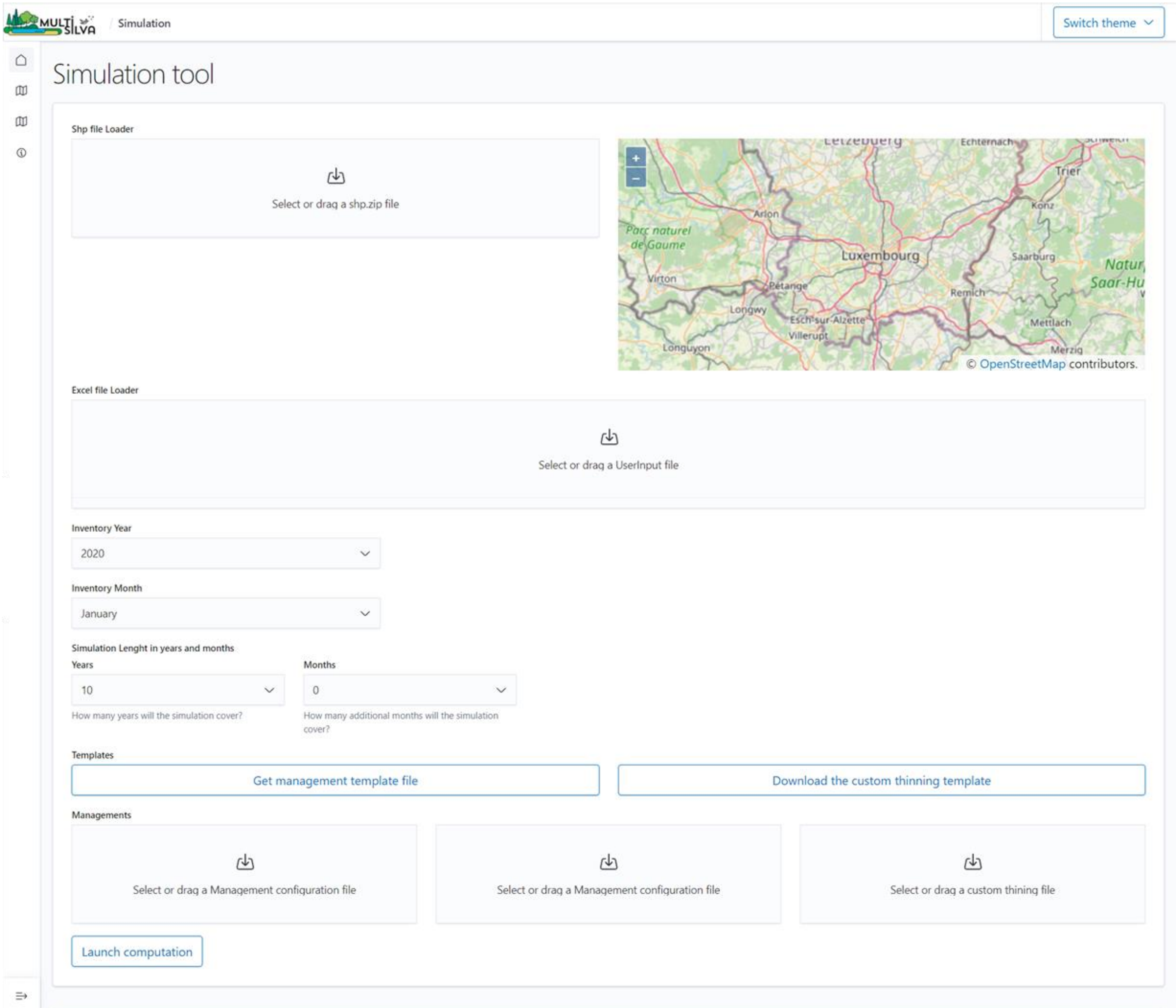

Figure 4. The user interface of the Simulation tool.

The first input required, i.e., the zipped folder (.zip) containing the shapefile of the forest property and its subdivision in management units, determines the area to be simulated. It suffices to provide a shapefile with management units that need to be simulated (using external GIS software) and upload it to the shapefile loader. The tool will automatically filter out the inventory data for the management units that are not present in the shapefile, making it easier to analyse a sub-portion of a forest property.

The management actions are defined via an Excel file, a template for which is available through the web interface. This management template comprises a sheet in which the user can activate the six management actions: harvesting, thinning, young stand cleaning, habitat tree retention, setting aside a stand, and trail maintenance. Once an action has been activated, the action's parameters must be set in the specific sheet. The parameters are presented in Table 2. Thinnings are based on standard itineraries (based on local silvicultural guidelines). It is possible to modify the itineraries by downloading the thinning template, setting up the desired basal area targets, and uploading the file via the user interface.

Table 2. Management actions and expected links to ES provision.

Management Actions	Parameters	Expected Effect on ESs
Harvest	*Granularity*: stand, species, and age group. • The species and age group to be removed; • Year and month of the harvest; • The type of harvest (continuous-cover forest or gap); • The type of regeneration (natural or artificial); • The type of protection for the regeneration (fencing, single tree protection, or removal of competition).	*Positive:* Timber production *Negative:* Carbon sequestration Recreation Air quality Biodiversity *Case specific:* Water protection
Thinning	*Granularity*: stand, species, and age group. • The type of thinning: standard (following the recommended thinning itineraries) or custom (user-defined via the specific template).	*Positive:* Timber production *Negative:* Carbon sequestration Recreation Air quality *Case specific:* Water protection
Young stand cleaning	*Granularity*: stand and species. • Initial and final age for pre-commercial thinning; • Frequency of the interventions.	n.a.
Set aside	*Granularity*: stand. • Stand to be set aside.	*Positive:* Biodiversity Recreation Air quality *Negative:* Timber production *Case specific:* Water protection
Habitat trees	*Granularity*: stand, species, and age group. • Number of trees per hectare to be retained as habitat trees.	*Positive:* Biodiversity Recreation Air quality *Negative:* Timber production *Case specific:* Water protection
Trail maintenance	*Granularity*: stand.	*Positive:* Recreation

	• Type of maintenance: none, low (only path maintenance), or high (path and infrastructure maintenance).	
Management of stands in regeneration phase at period 0	<u>Granularity</u>: stand, species, and regeneration age. • The type of protection for the regeneration (fencing, single tree protection, or removal of competition); • Whether young stand cleaning is carried out or not.	n.a.

The tool automatically fills in the stand identifiers, the species within each stand, and the management classes within each management action to aid the user in setting up management alternative.

The tool can simulate two management alternatives simultaneously; it suffices to load the completed management templates. The templates are spreadsheets in XLS format (a commonly used format among forest practitioners). The use of a spreadsheet allows management template files to be easily stored and the parameter set to be recalled to replicate the same simulation over time.

Once the simulation is completed, the tool shows two result tables: the first table compares the cumulative values of the ES indicators under the two management alternatives, and the second table presents the direct and indirect economic costs as well as the revenues for each management alternative (the full list of ES indicators and economic values is presented in Table 3). The economic values are computed from the biophysical ones using predefined parameters, which include timber prices for each tree species, as well as costs associated with planting, fencing, thinning, harvesting, and trail maintenance. The user has the option of changing any values in the template provided. Both the ES indicators and the economic values are aggregated at the forest property level. The tool offers the possibility to download the disaggregated results in a spreadsheet format. ES indicators and economic values can be further analysed at a monthly resolution for each management unit within the forest property. A graphical comparison of the two management alternatives is offered by a radar plot of ES indicators, individually rescaled on a scale of 1 to 10 to provide meaningful visualisation.

Table 3. Indicators and economic parameters included in Multisilva.

Ecosystem Service Indicators	Unit	Economic Values	Unit
Total extracted timber	m^3	Timber revenues	EUR
Variation in standing volume	m^3/ha	Harvesting costs	EUR
Air pollution deposition	t of PM_{10}	Planting costs	EUR
Water purification	t of N	Young stand cleaning costs	EUR
Total carbon sequestered	t of CO_2-eq	Recreational-service-related costs	EUR
Recreation (average WTT over the simulation)	km	Set aside opportunity costs	EUR
Recreation (final WTT)	km	Habitat tree opportunity costs	EUR
Average relative true diversity	Eq. number of species		
Relative true diversity (min and max, final period)	Eq. number of species		
Area set aside	ha		
Average number of habitat trees per hectare	Habitat trees/ha		

2.4.2. The Background Models

At the core of the Simulation tool is the forest growth simulator. There are two main modelling families to describe the evolution of a forest stand: on the one hand, empirical models, based on statistical methods applied to observed data [30–32], and on the other hand, process-based models, based on explicit processes and interactions in forest ecosystems [33,34]. The Simulation tool behind Multisilva is a process-based forest growth model that can represent mixed and uneven-aged forests [35,36]. In this regard, process-based models explicit represent processes and interactions in forest ecosystems such as the carbon, water, and nutrient cycles and can capture the effects of changing climatic conditions. These processes are strictly linked with the provision of ESs, and consequently, a process-based approach was selected for the Simulation tool calculations. Considering the targeted spatial scale of the tool (forest estate level), stand-level models were preferred to tree-level models [37] in order to maintain a fast computing time and keep the model parameter set at a reasonable size.

We leveraged the literature review conducted by Pretzsch et al. [36] of the existing forest growth models to identify the forest model best suited to develop the decision support system. From the list of 54 forest growth models, the 3-PGmix model [34] was selected for the following reasons: (i) it was process-based, hence capable of simulating variations in forest dynamics due to management or changing climatic conditions; (ii) it was able to represent mixed-tree-species iterations; and (iii) it was equipped to describe essential processes related to radiation, water, phenology, and nutrient dynamics, which are critical for developing ecosystem service indicators. Although other models like BALANCE [38], 4C [39], and ANAFORE [40] met these criteria, 3-PGmix was preferred due to its larger number of species with pre-calibrated parameters and its lower requirement for detailed input data. This choice came at the expense of individual tree modelling; however, the cohort-level structure made it computationally efficient while retaining the capacity to model essential interspecies interactions.

The 3-PGmix model derives from the 3-PG model developed by Landsberg and Waring [41], and since then, it has been validated for many species and regions around the world. The 3-PGmix model has a monthly time step and consists of five sub-models in a causal chain. These are described in detail by Forrester et al. [42], and only an overview is given here. The first sub-model predicts light absorption [43] and from that estimates gross primary production (GPP) with corrections imposed by temperature, frost, vapour pressure deficit (VPD), soil moisture, soil fertility, atmospheric CO_2, and stand age. Net primary production (NPP) is then calculated assuming NPP/GPP = 0.47 [44].

In the second sub-model, the NPP is distributed to foliage, stems, and roots. The third sub-model calculates density-dependent mortality using the −3/2 self-thinning law to adjust the number of trees per hectare [45–47]. The water balance is calculated in the fourth sub-model, using a species-specific canopy conductance, leaf area index (LAI), and any limitations caused by VPD, soil moisture, atmospheric CO_2, and stand age. The fifth and final sub-model converts biomass into output variables such as tree diameter, height, basal area, and wood volume.

Additionally, 3-PGmix requires the relationships governing species-mixing proportions to be provided [34]. For example, species contributions to the total stand LAI are necessary to calculate canopy interception and canopy conductance. In particular, the differentiation between deciduous and coniferous species is critical, with two parameters defining the month when leaves are produced and the month when they are lost required for deciduous trees.

The original, freely available 3-PGmix model was implemented in Python and adapted to meet the specifications of the Simulation tool. The resulting model was called "3-PGmix—Multisilva". The novelties of the 3-PGmix—Multisilva are as follows:

(a) Management actions to improve specific ESs and modelled to represent the current practice in Luxembourgish forestry were added. Specifically:
- Thinning and harvesting functions;
- Stand regeneration management actions;
- Management actions to promote biodiversity;
- Management actions to promote forest recreation.

(b) The forest growth model was enriched by five ES modules linking the variables from the process-based growth model and the management model with dynamic ES provision models from the literature:

- Carbon storage, computing the below- and above-ground carbon stored in the biomass as well as the soil organic carbon [48];
- The air purification module, computing the tons of PM_{10} intercepted by the canopy [49,50];
- The water quality module, computing the tons of nitrates sequestered from or released into the soil by the forest [51];
- The forest recreation module, computing the attractiveness of the forest measured as a WTT to visit the forest [52] combined with a distance-dependent, decreasing logistic function to account for the accessibility of the forest stands;
- The biodiversity module, computing three biodiversity indexes [53]: the Shannon Index based on tree species richness, the tree size diversity index at the stand level, and the habitat tree index.

(c) A regeneration module was added to predict the regeneration success, via a generalised ordered logit model fitted to the inventory data of Luxembourgish forests.
(d) An economic module to compute revenues, costs, and opportunity costs over the simulation.
(e) An automatised model initialisation system.

Leveraging the recent availability of species-specific parameters for European tree species [54], the tool can simulate the growth dynamics of the following species: European beech (*Fagus sylvatica*), sessile oak (*Quercus petraea*), pedunculate oak (*Quercus robur*), European ash (*Fraxinus excelsior*), sycamore maple (*Acer pseudoplatanus*), birch (*Betula spp.*), Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*), Douglas fir (*Pseudotsuga menziesii*), European larch (*Larix decidua*), European silver fir (*Abies alba*), and Swiss pine (*Pinus cembra*). These species represent most of the standing volume in Luxembourg [55]. The remaining species are assigned into one of the following species groups:

- "Noble broadleaves": e.g., *Carpinus* spp., *Juglans* spp., *Sorbus torminalis*, and *Prunus avium*.
- "Other broadleaves": all broadleaved species not included in the "noble broadleaves" group (e.g., *Alnus* spp., *Popolus* spp., *Salix* spp., and *Sorbus* spp.).
- "Other conifers": all remaining conifer species (e.g., *Abies* spp. and other *Pinus* spp.).

An internal function of the tool automatically converts the species codes used in forest inventories in Luxembourg to match the Multisilva codes; by editing this function, the tool can be adapted to any temperate forest region in Europe.

3. Illustrative Example

3.1. The Study Area

To illustrate some capabilities of the Multisilva simulator, a case study of a forest area near Flaxweiler in eastern Luxembourg (Figure 5) is presented in this section. The area used in this example is a subset of a larger set, visible in Figure 3. The subset covers 27.6 ha of forest and is made up of 12 individual management parcels (stands). Six of the tree species listed in the previous section are present, along with the three "other" species group classifications (Table 4). This section of the forest contains the sources of the Donwerbach river, a tributary of the Moselle. The majority of the study area (24.1 ha) is part of the Widdebierg-Hierden Nature Reserve, with several footpaths and a mountain bike trail providing opportunities for recreation.

Table 4. Tree species summary in the study area.

Species	Latin Name	# Trees
European beech	*Fagus sylvatica*	1776
Sessile oak	*Quercus petraea*	2070
Douglas fir	*Pseudotsuga menziesii*	262
European spruce	*Picea abies*	1160
European ash	*Fraxinus excelsior*	89
European larch	*Larix decidua*	43
Noble broadleaves		24
Other broadleaves		455
Other conifers		47

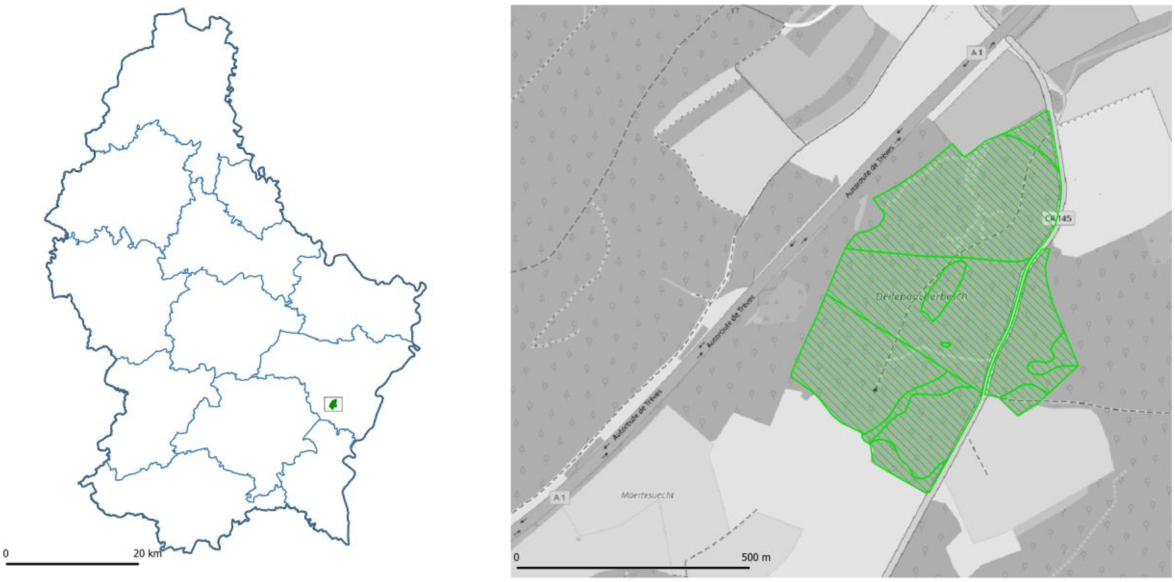

Figure 5. The Flaxweiler study area in Luxembourg.

3.2. Management Scenarios and Uncertainty

In this example, different management strategies are considered. For each of them, a 10-year simulation period, starting in January 2024, is calculated with identical initial starting conditions. The annual discount rate is fixed at 3%, the maximum slope for harvesting is 40 degrees, the percentage of bark and branches as fuelwood is 50%, the maximum diameter for firewood is 15 cm, and the annual loss to recreation without trail maintenance is set at 2%. In the first (base) case, no management actions are planned for the duration of the simulation. To identify reasonable management actions, the study area was then examined using the Mapping tool, with two potential hotspots identified (Figure 6). Two stands (35.1 and 35.2) were found to have significant overlap with the waterbodies (the Donwerbach and its tributaries). Furthermore, the hiking and cycling paths within (and along the border of) the area are clearly visible.

One of the management actions considered is the removal of conifers in the areas overlapping water bodies to improve the water purification potential. In parcel 35.1, there are spruce trees determined to be 55 years old during the 2017 inventory, which corresponds to the rotation age of 60 recommended by the Luxembourg Ministry of Environment [55]. Furthermore, oaks in parcel 33.1 are recorded as 180 years old in the inventory. Given the rotation age of 200 years [55], their harvest also represents a reasonable management option. For the illustrative purposes of this case study, harvests of both these tree groups will be considered in some simulations, set to be performed in October 2026, with post-harvest cleaning taking place, followed by natural regeneration. A further parameter incorporated into the simulations is the investment in the maintenance of hiking and cycling trails. It is not the contention of the authors to promote any of these strategies; the parameters have been chosen purely for the purpose of illustrating the functionality of the software.

Figure 6. Flaxweiler hotspots identified with the Mapping tool. (**Left**) recreation potential; (**right**) overlap with water bodies.

An important source of uncertainty in forest management planning is forecasting of the future climatic parameters [22,27,56]. To address this, the software gives the user an opportunity to consider several meteorological scenarios. This is optional; if no such scenarios are provided, the climatic parameters will be obtained from the background data (as described in Section 2.4), and the output will contain single values for each predefined ecosystem service indicator for each management alternative. When alternatives are specified, by attaching a filled-in template file containing the details of each forecast, additional simulations will then be performed. In the output, ES indicators will then consist of ranges for each management alternative, giving an indication of the uncertainty associated with each indicator and allowing for more meaningful comparison of the results of management strategies. In the example here, five climatic scenarios were considered in addition to the core one: an increase in precipitation by 25%, a decrease by 25%, and three scenarios with a temperature increase of 0.2 degrees, and the rainfall unchanged, increasing, and decreasing by 25%. These values are only for illustrative purposes; users will have the opportunity to specify detailed parameters according to forecasting scenarios of their choice.

A further source of uncertainty is the parameter specifying the site fertility rating (FR). While this indicator contains information about the quality of the soil and features in the 3-PG algorithms, it is a subjective estimate, with approaches for its estimation ranging from expert opinion to soil chemistry studies [57–59]. In Multisilva, this parameter is one of the input parameters required in the management scenario template. Users thus have the possibility to estimate this parameter using any methods they see fit, and to examine the effects of this rating on the results; this can be performed by submitting two management templates differing only through this parameter. The original simulations were carried out with FR assigned a value of 0.5, with further simulations using FR = 0.8 performed to illustrate possible effects of the fertility parameter.

3.3. Results

The results for selected simulated ES indicators and economic parameters are given in Table 5. Indicators which do not change with varying climatic parameters are presented as individual values (e.g., extracted timber and revenues), whereas parameters exhibiting variations are given as ranges. For instance, for the case including harvests, no trail maintenance, and FR = 0.5, the water purification indicator varies between 5.1 and 5.4 tons of sequestrated nitrates, depending on the climate scenario. This entire range is lower than the span of values in the case of no harvesting (5.4–5.6 tons), showing that while the exact value cannot be predicted, the effect of harvesting will be detrimental to water purification potential if no other actions are considered. On the other hand, the range overlaps with the one obtained using FR = 0.8 (5.2–5.5 tons), suggesting that no clear correlation can be derived. The amount of sequestrated carbon decreases when harvests are performed, as only standing stock is considered when calculating sequestration.

Table 5. Results for selected ES indicators.

ES indicator	Unit	No Harvest No Maint. FR = 0.5	Harvest No Maint. FR = 0.5	Harvest No Maint. FR = 0.8	No Harvest Maint. FR = 0.5	Harvest Maint. FR = 0.5
Total extracted timber	m^3	0	2600	2600	0	2600
Timber revenues	EUR	0	9440	9440	0	9440
Recreation costs	EUR	0	0	0	16,640	16,640
Air pollution deposition	Ton PM_{10}	2.1	1.9	1.9	2.1	1.9
Water purification	Ton N	5.4–5.6	5.1–5.4	5.2–5.5	5.4–5.6	5.1–5.4
Carbon sequestrated	Ton CO_2-eq	1300–1360	1190–1250	1220–1280	1300–1360	1190–1250
Recreation (average WTT)	km	5.8–6.1	5.9–6.2	5.9–6.2	9.3	9.4

4. Discussion and Conclusions

Multisilva, a forest management DSS, has been developed to support forest managers in addressing the demand of ESs from local stakeholders, to understand the trade-offs between different management alternatives, and to communicate the management strategy and the expected outcomes in a straightforward way. For these reasons, Multisilva could be a useful tool to support the definition and design of ES validation claims, such as the ones recently introduced by the FSC. The novelties of Multisilva, compared to existing forest management DSSs, are (i) the focus on multiple ecosystem services and the specific focus on forest management for ES provision and (ii) the coupling of different models (3PG-mix and the different ES models) under one single simulation coordinated over a time computational model. The system presented here is based on a process-based forest growth model (3PG-mix), which has been extended to account for six ESs: air quality, carbon sequestration, timber production, water protection, biodiversity conservation, and outdoor recreation. The Mapping tool of the system allows for visualisation and calculation of statistics of the current provision of these ESs. This supports the user in identifying ES hotspots, which can then be examined in more detail with the Simulation tool, which models a series of management actions such as thinning, trail maintenance, habitat tree retention, selective harvesting, and setting aside areas for nature conservation.

A 27 ha forest plot near Flaxweiler in eastern Luxembourg has been used to demonstrate the functionality of the Simulation tool. In addition to defining various management strategies to consider, the user has the option to specify possible future climate scenarios. The tool then calculates the ES indicators for each scenario, providing a level of uncertainty for the results. Comparison of these ranges for various management strategies allows the user to determine whether any differences in the simulated results are statistically significant.

The current version (v0.1.6) requires shapefiles of the area and Excel files containing the forest inventory. Possible improvements in the future could include remote data acquisition, eliminating the need for field work. The current version is developed for Luxembourg, and it is particularly well suited for extension to temperate and boreal forest regions, where only minor adjustments are needed (formatting of the inventory data and adaptation of management practice parameters). The Simulation tool could readily be adapted for application across Europe by leveraging widely accessible datasets, including meteorological data, air quality records, elevation models, and open map services. Given the availability of species-specific parameters, the tool shows strong potential for adaptation to temperate and boreal zones, making these regions especially promising for immediate implementation. For Mediterranean areas, however, the major limitation today is the lack of species-specific parameters, with only two pine species available to the best of our knowledge. For tropical areas, the tool's adaptability would face additional challenges primarily due to limited species-specific parameter data and differences in forest dynamics compared to temperate or boreal regions. While some parameters are available for common tropical species like *Eucalyptus* and *Tectona grandis*, many tropical species lack the necessary calibration, which could impact the precision of ES simulations in these biodiverse forests. Additionally, tropical regions often experience distinct climatic conditions, such as high rainfall and unique seasonal cycles, which would require careful tuning of hydrological and growth models within the DSS. However, with targeted data collection and adaptation, the Multisilva DSS could eventually support tropical applications, especially in more managed tropical forests where available species data may align with existing model parameters.

The mapping functionality within Multisilva is a robust spatial analysis tool, and with access to spatially explicit maps of ecosystem service supply, it would be straightforward to extend this capability to other regions beyond Europe, enabling a broader application of the tool in supporting forest ecosystem service provision.

In the long run, the DSS can be tailored to help forest owners to identify potential customers of ESs, and hence set the path towards the implementation of payment of ecosystem services, or alternatively to support ES certification procedures by offering the ability to simulate the impact of specific management practices with respect to a business-as-usual scenario.

Supplementary Materials: The following are available online at www.mdpi.com/xxx/s1, Table S1: Assessment of tools listed on the Forest DSS Community of Practice. Sheet 1: List of all tools. Sheet 2: Selection of tools able to model ESs or forest management.

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Data Availability Statement: The links to geospatial data sources are provided in Table A1 in Appendix A.

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Appendix A

This appendix presents the details concerning the background data and methods used to assess the current provision of cultural, supporting, and regulating ESs through the proxies and indicators used in the Mapping tool.

Appendix A.1. The Functions Nature Protection Areas, Water Protection, and Water Bodies

The functions "Nature protection area computation", "Water protection computation", and "Water bodies computation" were coded in Python, taking advantage of the *geopandas* package functionalities (https://geopandas.org/, accessed on 24 November 2024). These three functions compute the percentage of the surface of each management unit (stand) overlapping with a specific background shapefile covering the entire territory of Luxemburg.

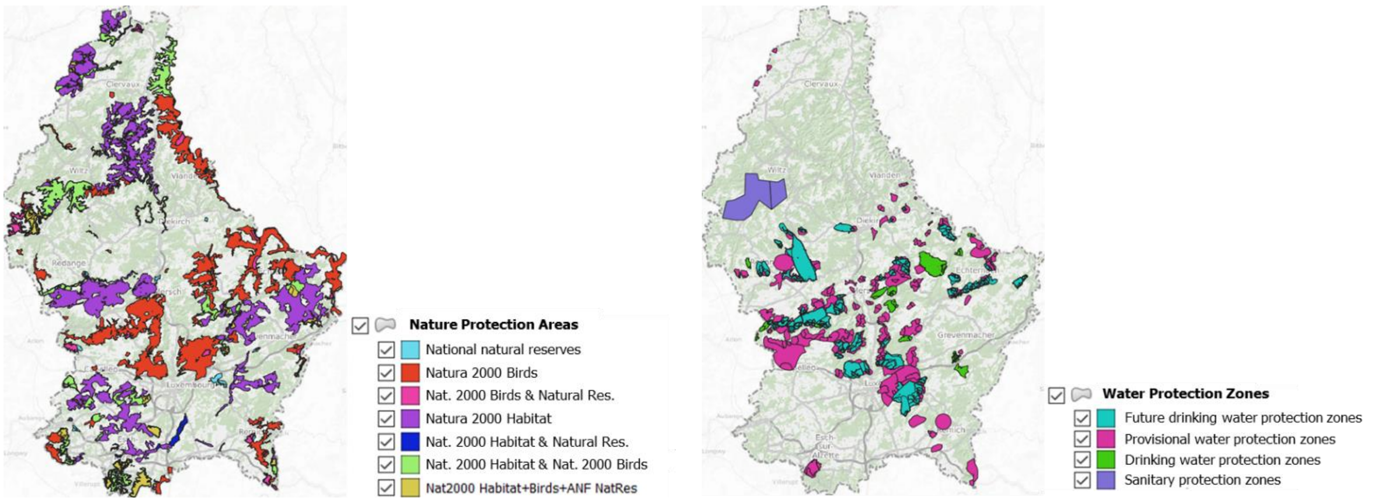
Table A1 shows the input files used to generate the background maps. Concerning the "Nature protection area computation" function, the background shapefile was generated by the combination of three datasets on nature protection areas downloaded from the open data repository https://data.public.lu/en/ (accessed 24 November 2024). Because the three original datasets on protected areas were overlapping, the nature protection area shapefile kept track of these overlaps (i.e., forests falling into two or more protection zones). Similarly, the "Water protection computation" function used a background map that was the result of the intersection between input datasets of drinking and sanitary protection zones. In this case, there was no overlapping between the different zones. Figure A1 shows the resulting background maps for the two functions.

Table A1. Nature protection area background data.

Function	Input Dataset	Link	Last Access
Nature protection areas	Protected areas under the Nature 2000 Habitats directive	https://data.public.lu/fr/datasets/r/7891229f-f37c-463c-97db-987fa6a65e64	24 November 2024
	Protected areas under the Nature 2000 Birds directive	https://data.public.lu/fr/datasets/r/57e9f6fa-fd1f-4ca7-a943-de8d009dd700	24 November 2024
	National nature reserves and integral forest reserves	https://data.public.lu/fr/datasets/r/340cc93d-d38a-45f3-9491-29749fe531ac	24 November 2024
Water protection	Provisional drinking-water protection zones	https://data.public.lu/fr/datasets/r/2becbf19-b767-4ebc-8dea-5229f3c484f7	24 November 2024

	Drinking-water protection zones,	https://data.public.lu/fr/datasets/r/f63f4c2b-c6fb-44d1-bbae-4805dbf12a61	24 November 2024
	Upper-Sûre lake protection zones	https://data.public.lu/fr/datasets/r/cb9386a3-0e51-48f1-a36b-1dbb9f62a56b	24 November 2024
Water bodies	GeoConnectGR: lakes and reservoirs	https://data.public.lu/fr/datasets/r/852d8da4-4a50-49cc-a43a-8ec59f9f5bb8	24 November 2024
	GeoConnectGR: areal water courses	https://data.public.lu/fr/datasets/r/71ea511f-42e6-4edb-98b9-c3e8a5232875	24 November 2024

The function "Water bodies computation" builds a buffer with a user-defined width (the pre-set width is equal to 50 m) around each surface water body. These surface water bodies comprise a background shapefile that is the result of the merging of two publicly available datasets (see Table A1). Once the buffer areas are generated, the function returns, for each management unit, the percentage of the area intersecting the buffer.



(**a**) (**b**)

Figure A1. The background maps used by the functions: (**a**) nature protection area computation; (**b**) water protection zone computation.

Appendix A.2. Functions Based on the Species Distribution Models

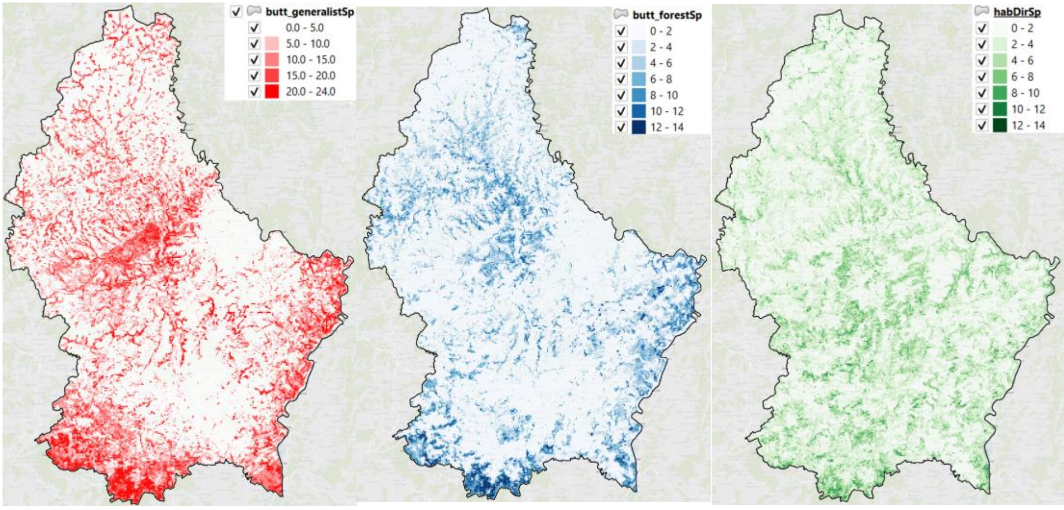
The functions "Launch Butterflies forest specialist computation", "Launch Butterflies generalist computation" and "Launch Habitat directive species computation" return the number of protected species and the species names per management unit. These estimations are based on the species distribution models (SDMs), which combine presence records of a species with spatially explicit environmental variables (e.g., temperature, precipitation, topography, geology, and land use) and control for the bias introduced by direct field observations. The SDM data are stored as shapefiles (200 m squared polygons) covering the entire territory of Luxembourg. For each grid cell of the study area, the SDM returns a habitat suitability index (values between 0 and 1), reflecting the probability of presence of the species. The determination of a threshold allows this index to be binarised afterwards in order to consider a species as present (index values above the threshold) or absent (below the threshold) in each grid cell. The threshold is computed using the maximum training sensitivity plus specificity logistic threshold [60]. The same threshold methodology is used for all the species.

From the 85 butterfly species with national distribution knowledge, 14 species are highly related to forest biotopes, and 27 are generalist species related to forest biotopes, open woodlands, and grassland. Concerning the Habitat Directive protected species, SDMs were produced for all species that had enough field observations, but not all models passed the experts' evaluation and hence could not to be used for reporting under article 17 [27]. Overall, the SDMs for 19 species were included in the tool. The complete lists of species included in the three functions ("Launch Butterflies forest specialist computation", "Launch Butterflies generalist computation", and "Launch Habitat directive species computation") are presented in Table A2.

Based on the SDM for the 60 selected species (14 forest-specialist butterflies, 27 generalist butterflies, and 19 Habitat Directive species), it was possible to generate 60 grid shapefiles containing presence–absence data for each species. These grids were aggregated into three shapefiles (one for each of the three functions). These three shapefiles used the same 200 m grid and contained for each cell the total number of species present (of forest-specialist butterflies, of generalist butterflies, and of Habitat Directive species) and their Latin name. The background aggregated SDMs are shown in Figure A2.

Table A2. List of species for which a validated SDM is available.

Forest-Specialist Butterflies	Generalist Butterflies	Habitat Directive Species
14 species	27 species	19 species
	Aglais io	
	Aglais urticae	
	Anthocharis cardamines	
	Aphantopus hyperantus	
	Araschnia levana	*Alytes obstetricans*
	Coenonympha pamphilus	*Coronella austriaca*
Apatura ilia	*Gonepteryx rhamni*	*Dicranum viride*
Apatura iris	*Issoria lathonia*	*Euplagia quadripunctaria*
Argynnis paphia	*Lasiommata maera*	*Felis silvestris silvestris*
Brenthis daphne	*Lasiommata megera*	*Helix pomatia*
Callophrys rubi	*Leptidea sinapis*	*Lacerta agilis*
Carterocephalus palaemon	*Lycaena phlaeas*	*Leucobryum glaucum*
Celastrina argiolus	*Maniola jurtina*	*Lycaena dispar*
Favonius quercus	*Ochlodes sylvanus*	*Lycaena helle*
Limenitis camilla	*Papilio machaon*	*Maculinea arion*
Nymphalis polychloros	*Pieris brassicae*	*Martes martes*
Pararge aegeria	*Pieris mannii*	*Muscardinus avellanarius*
Satyrium ilicis	*Pieris napi*	*Pelophylax esculentus*
Satyrium pruni	*Pieris rapae*	*Pelophylax lessonae*
Thecla betulae	*Polygonia c album*	*Podarcis muralis*
	Polyommatus icarus	*Rana temporaria*
	Pyrgus malvae	*Sphagnum* L. spp.
	Pyronia tithonus	*Triturus cristatus*
	Thymelicus lineola	
	Thymelicus sylvestris	
	Vanessa Atalanta	
	Vanessa cardui	



(**a**) (**b**) (**c**)

Figure A2. Aggregated SDM for the (**a**) generalist butterflies, (**b**) forest-specialist butterflies, and (**c**) Habitat Directive species.

In order to compute the species presence at the stand level, the three functions read the values in the cells overlapping with every stand and count the number of unique species. For example, imagine a stand that overlaps with three cells of the Habitat Directive aggregated SMD: cell 1 indicates the presence of three species *Dicranum viride*, *Euplagia quadripunctaria,* and *Felis silvestris silvestris*; cell 2 indicates the presence of *Felis silvestris silvestris* and *Helix pomatia*; and cell 3 indicates the presence of *Dicranum viride* and *Helix pomatia*. Therefore, the three cells overlapping with the stand contain four unique species: *Dicranum viride*, *Euplagia quadripunctaria*, *Felis silvestris silvestris,* and *Helix pomatia*.

Appendix A.3. The Recreation Computation

In the Mapping tool, the landscape potential to provide recreational enjoyment depends on people's preference for certain activities and the non-urban areas' characteristics. Consequently, the value attached to specific landscape elements varies depending on the type of recreationists. Different types of recreationist groups are identified in the literature, starting from the seminal work of Cohen [28]: "convenience recreationist", "day tripper", "education recreationist", "nature trekker", and "spiritual recreationist". Each group is characterised by different motivations, needs, and preferences. The most common user groups in Luxembourg were selected as references: (i) convenience recreationists and (ii) sport recreationists (adapted from Cohen's "day tripper").

The "Recreation computation" function in the Mapping tool is based on the work of Komossa et al. [29], with the focus on the two selected user groups. This framework was adapted to the Luxembourgish context. A score between 1 (low) and 5 (high) was assigned to a specific area (in our case, a 10 m × 10 m pixel) reflecting the potential for outdoor recreation of a specific user type. Table A3 presents in detail the outdoor recreation needs for the two groups and how these needs are translated into recreational preferences. The landscape attributes were approximated with landscape proxies. For each attribute, an "attribute" raster file was generated based on the identified spatial proxy.

Table A3: Outdoor recreation parameters

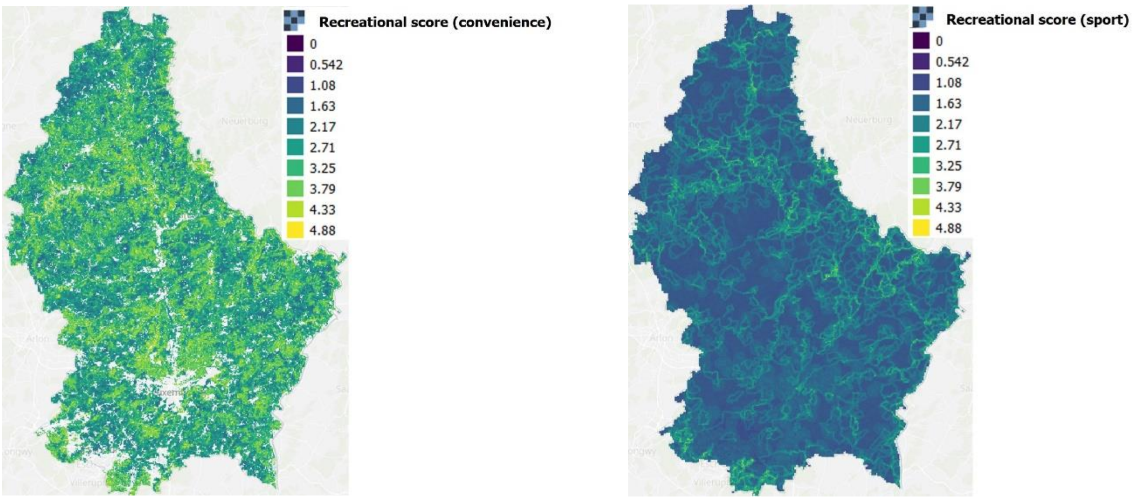
Recreational Needs	Landscape Preference	Landscape Attribute	Spatial Proxies
		Convenience recreationists	
Relieve tension from everyday life	Convenience recreationists prefer a landscape with a high level of	Vegetation variety	Land cover composition, preference for broadleaved and mixed forests, natural

through easy short-term leisure activities close to the place of residence.	attractiveness or scenic beauty, possibly with proximity to water and accessible via paths or trails. Distance from home less than 500m.		surfaces (natural grasslands, rocks, and wetlands). Not attracted by intensive agriculture and forestry (clear-cuts and young plantation).
		Water proximity	Distance form surface water bodies (both natural and artificial).
		Pollution	PM_{10} concentration maps. Distance from main roads.
		Accessibility	Presence of marked or unmarked paths and trails.
Sport recreationists			
Escape from the stressful routine of everyday life through active and sportive experiences of nature. These activities are generally longer than those of convenience recreationists.	Sport recreationists seek landscapes whose characteristics allow for outdoor sport recreation (running, Nordic walking, cycling, mountain biking, orienteering, etc.). Marked tracks, air quality, and accessibility are important elements. Sport recreationists are willing to travel longer distances by car to reach the recreational areas, within 8 km.	Outdoor sport facilities	Presence and distance from: - Short-distance marked paths. - Long-distance marked paths. - Bike paths.
		Pollution	PM_{10} concentration maps. Distance from main roads.
		Accessibility	Distance from public car parking.

A specific attribute score was assigned to each pixel of the raster based on the characteristics of the proxy. For instance, for sport recreationists, the "Accessibility" attribute was measured using the proxy "Distance from public car parking". A score from 0 to 5 was assigned as a function of the distance from the specific pixel to the nearest parking site. The resulting scores for the single attributes were then aggregated using attribute weights to compute the final recreational potential scores for the two types of recreationists. For each pixel, the potential recreational score for a recreational type r (with r assuming the values "sport recreationist" and "convenience recreationist") was obtained as follows:

$$Score_{r,i} = \sum_{k=1}^{N} w_{r,k} \times attribute_{k,i}, \quad \text{(A1)}$$

where $attribute_{k,i}$ is the value of attribute "k" in pixel "i" (e.g., "Pollution—Distance from main roads", "Accessibility—Long distance marked path", etc.), "N" is the total number of attributes, and $w_{r,k}$ is the weight assigned to the attribute by the recreationist group "r" (i.e., the importance of that attribute for the overall recreational score). The weights assigned to each attribute must add up to one. Figure A3 shows the raster files with the aggregated scores for the two recreationist groups.



(**a**) (**b**)

Figure A3. The background maps of the recreation computation function: (**a**) outdoor recreational potential scores for the convenience recreationist group; (**b**) outdoor recreational potential scores for the sport recreationist group. Both maps are based on the work of Komossa et al. [29]. Urban areas are not considered for convenience recreation.

Once the raster files with the total scores were generated, they were normalised from 0 to 1 based on the maximum and minimum values observed in Luxembourg. The function "Recreation computation" then computes the average recreational potential of the pixels within each stand for the two recreationist types using the package *rasterstats* in Python.

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