Article

Solving Multi-Objective Problems for Multifunctional and Sustainable Management in Maritime Pine Forest Landscapes

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Abstract: Forest management based on sustainability and multifunctionality requires reliable and user-friendly tools to address several objectives simultaneously. In this work we present FlorNExT Pro®, a multiple-criteria landscape-scale forest planning and management computer tool, and apply it in a region in the north of Portugal to find optimized management solutions according to objectives such as maximization of net present value (NPV), volume growth, and carbon storage, and minimization of losses due to fire. Comparisons made among single- and multi-objective solutions were made to explore the range of possible indicators provided by the tool such as carbon sequestered, volume growth, probability of fire occurrence, volume of wood extracted, and evenness of harvesting in the management period. Results show that FlorNExT Pro® is a reliable, flexible, and useful tool to incorporate multiple criteria and objectives into spatially explicit complex management problems and to prepare sustainable and multifunctional forest management plans at the landscape level. FlorNExT Pro® is also suited to guiding and adapting forest management for uncertainty scenarios for the assessment of ecosystem services and fire risk, therefore playing an important role in the maintenance of sustainable landscapes in the south of Europe.

Keywords: operational research; optimization; carbon sequestration; spatially explicit forest management planning; decision support systems; Portugal

1. Introduction

Forests support many ecological functions that contribute to the supply of diverse high-value ecosystem services (ESs), thus directly and indirectly benefiting human societies [1]. Many of these ecosystem services are synergic and they can be supplied and used simultaneously. Examples include timber—carbon sequestration [2], or water regulation/supply—carbon sequestration [3]. In other cases, the supply of one or several ESs implies a reduction in the supply of others (e.g., [3,4]). Tradeoffs and synergies among ESs (or classes or bundles of ESs) are therefore significant management challenges considering that the potential conflicting supply of ESs needs to be taken into account in sustainable forestry planning. The integration of tradeoffs and synergies of ESs into forest decision support systems is a response to that need and is a growing research topic [5–7]. Observed advances in this field are foreseen as fundamental to supporting sound decision making at the site and landscape levels as well as to allow the integration of stakeholders with interests related to particular forest ESs in the areas of game, fisheries, tourism, timber, or water, in decision making processes.

The implementation of the ES concept and ES tradeoff analysis in forestry requires technology to simultaneously address diverse management criteria and indicators. There is a long tradition in

forestry of looking at management from multiple perspectives based on concepts such as multiple-use management [8], multifunctional forest management [9], landscape forestry [10], and ecosystem management and adaptive management [11] that involve management of forests considering multiple goals and objectives. This multiple approach to forest management is not always easy to plan and apply due to uncertainty (environmental, social, economic) but also to the general lack of knowledge in modeling and programing in the forest sector (particularly at the practice level) and to the lack of available tools that respond adequately to the needs of individual owners and managers, consultants, communities, and institutions in terms of planning and managing forests on a multiple-criteria multiple-objective basis.

Decision support systems (DSSs) are well established in forestry [12,13] and reviews of tools and resources concerning them are abundant (e.g., the ForestDSS web page at http://www.forestdss.org/, Forsys wiki [13], or FORSYS (Cost Action FP 0804 Forest Management Decision Support Systems)). DSSs help to detect optimal (or satisfactory if optimal is not reachable) solutions for specific goals and contribute to forest management focused on sustainability. The field of operational research (OR), originating during the Second World War and growing quickly in the last decades [14,15], provides fundamental tools to help find solutions for complex problems that are not possible to solve directly [16]. In OR, the use of optimization to support decision making approaches in sustainable forest management is an established field producing numerous methodologies and applications related to the topic [17–20], namely for species abundant in the Iberian Peninsula such as *Pinus sylvestris* [21], *P. pinaster* [22], *Quercus suber* and *Q. rotundifolia* [23], and *Eucalyptus globulus* [24].

Based on established programing and optimization methods and the long experience of development of DSSs in forestry, harvest scheduling models are a particular type of tool currently available with the purpose of supporting decision making based on the multiple-criteria approach. Examples include the model to address forest production and biodiversity conservation [25], the forest management scheduling model for timber and old forest production [26], spatial forest planning processes for volume, carbon, and spatial aggregation of management activities [27], and the planning method addressing wood production and hydrologic functions [28], among many others. Until recently, forest models had very limited transferability. There is, however, a trend of making forest planning and management computer models and tools simple, efficient, user friendly, open, and accessible to not just scientists but managers and owners as part of shared and transferable modeling and DSS technology development [29–31].

In the case of maritime pine, *Pinus pinaster*, there has been a substantial amount of research conducted in Portugal over recent years addressing decision support systems development based on multiple-criteria approaches [32–39]. However, the applicability of these models and approaches in the management of maritime pine landscapes requires further promotion. The objective of this research was to develop an accessible and easy to use multiple-criteria landscape scale forest planning and management computer tool (FlorNExT Pro®) to optimize forest management based on a combination of criteria and objectives as a response to the increasing need to put into practice forest management in a multifunctional, multi-objective, spatially explicit way. One of the components of the multi-objective problem is carbon sequestration in standing biomass that can be maximized at the landscape level through the application of FlorNExT Pro® within a climate change mitigation framework. Also, the probability of fire is a component of the objective function in the tool that can be used to minimize fire risk through planning and management of forest landscapes. Other components are net present value (NPV) and volume growth rate. The tool was applied in a region in northeastern Portugal with the goal of demonstrating the definition of optimized management plans for combinations and weights of management objectives, restrictions, and constraints, as well as prices of wood and discount rates. The development and application of FlorNExT Pro® is part of a regional strategy to increase technology transfer in forestry in northeastern Portugal.

2. Materials and Methods

In this section, we first present and describe the management tool developed in this research (FlorNExT Pro®) and then apply it to an area in the north of Portugal to demonstrate the establishment of forest management plans according to particular objectives or groups of objectives, restrictions, and constraints.

2.1. FlorNExT Pro®

FlorNExT Pro® is a computer tool developed with the aim of defining optimized management plans addressing simultaneously several (from a few to several hundred) maritime pine stands in northeastern Portugal, growing in heterogeneous conditions and according to several objectives, restrictions, and constraints (Figure 1). The tool is suited to combine a high diversity of stand conditions (slope, productivity, age, stocking) and several criteria and indicators in multi-objective and multifunctional forest management for a particular ecological region for which the same set of stand growth and yield models can be applied. Although FlorNExT Pro® was developed specifically for the northeast of Portugal using growth and yield models validated locally [31], it can be adjusted to any other region in the world as long as growth and yield models are available.
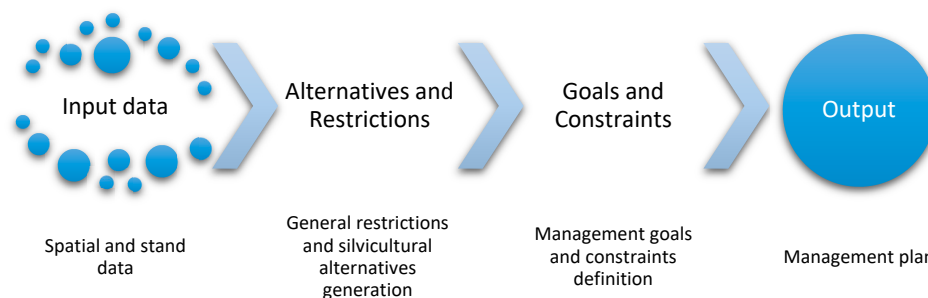

Figure 1. Simplification of the general management optimization procedure of FlorNExT Pro®.

The management plans outputted by FlorNExT Pro® consist of a sequence of spatially explicit forest operations to be applied within a specific period of time according to the management criteria and objectives as well restrictions and constrains imposed. The tool finds an optimal management solution among all the possible combinations of management practices (thinning, felling, and no treatment) to which stands are subjected to according to the number and amplitude of management intervals, delay between periods, and starting year, defined by the user. The following settings (Figure 2) are defined as:

- Number of periods: number of management periods (moments in time in which management operations—thinning, felling, or no-treatment—are applied);
- Maximum number of thinnings: maximum number of thinnings in each management unit or stand;
- Interval between operations: number of periods without management operations in each management unit or stand;
- Starting: year at which optimization starts;
- Amplitude: length of a management period, in years.

In the optimization process, all possible combinations of management operations at the stand level (management alternatives) are simulated and tested at the landscape level. The number of alternatives depends strongly on the number of periods and management practices prescribed. To reduce their number and make the process simpler and faster, some restrictions can be applied, such as the establishment of a minimum harvesting age and minimum and maximum thinning ages (Figure 2). The alternatives generated in this step will then be tested in all stands looking for an overall optimized management solution.
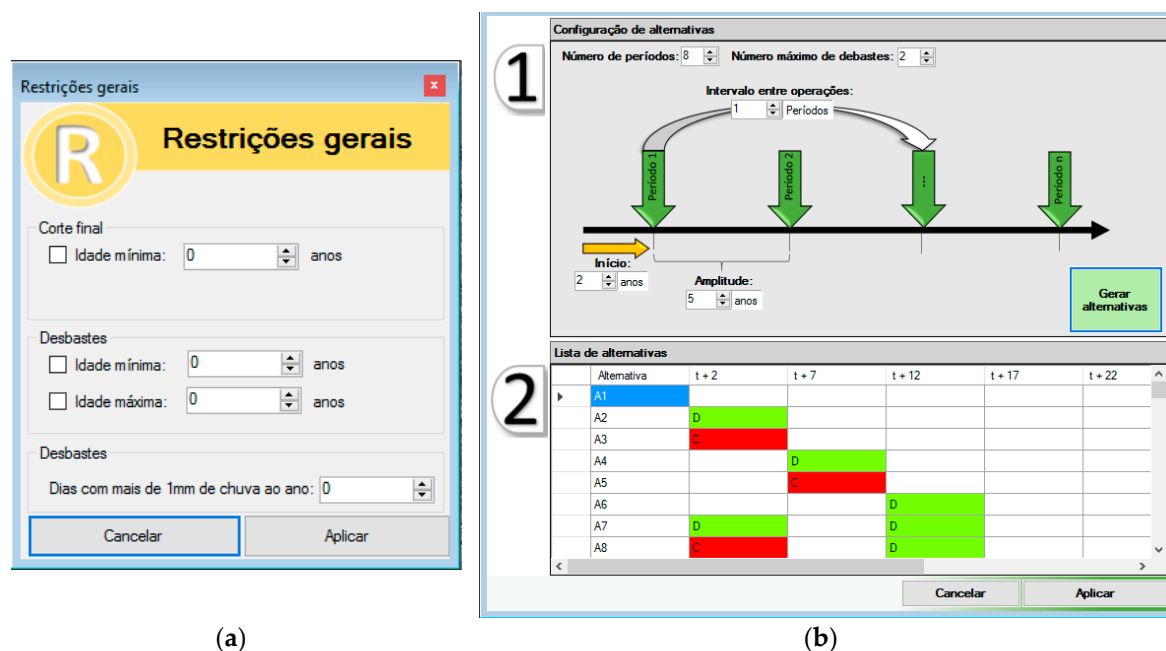
Figure 2. FlorNExT Pro® interface (in Portuguese) of the general restrictions (**a**) and management alternatives generator (**b**). General restrictions (*Restrições gerais*) include: minimum age for felling (*Corte final: Idade mínima*), minimum and maximum age for thinning (*Desbastes: Idade mínima; Idade máxima*), and number of days with more than 1 mm of rain for thinning (*Desbastes: Dias com mais de 1mm de chuva ao ano*). The management alternatives generator (*Configuração de alternativas*) requires definition of: number of periods (*Número de períodos*), maximum number of thinnings (*Número máximo de desbastes*), interval between operations (*Intervalo entre operações*), starting year (*Início*), and amplitude.

The tool operates based on two types of input data: spatial data and alphanumeric data. Spatial data consists of the geographical representation (location, area, topology) of all units or stands (represented as polygons) within a certain management area. It remains unchanged throughout the optimization process. Spatial data can be imported from conventional commercial or open source Geographic Information System (GIS) software or libraries like Gmap.Net linked with Google Maps, Bing, or OpenStreetMap. FlorNExT Pro® also gives the user the possibility to create, delete and edit polygons based on data from different map providers (Figure 3). This is particularly important in regions where no cadastral or detailed land use/land cover data is available. New/edited data can be saved as a FlorNExT Pro® project or exported in shapefile format. When edited, the geometry of each polygon is automatically recalculated and its area correspondingly updated. Each polygon is described according to a series of attributes managed by the user who can add/edit/delete fields in a table which can also be used for querying and selection of management units of interest.

Alphanumeric forest inventory data is used to describe quantitatively forest stands within the management area at the beginning of the management period. FlorNExT Pro® uses the following input inventory variables: year of the inventory; species; age (years); dominant height (m); density (trees/ha); basal area (m^2/ha); site index (40 years; m); average slope (%); and percentage of the stand covered by trees (%), if applicable. This data is required not just to define the condition of management units at year 0 of the optimization period but also to feed the forest growth and yield models coupled to the tool that will be used to project the condition of the stands over time. In its default version, FlorNExT Pro® applies models validated for the northeast of Portugal [31] for which it was originally designed.
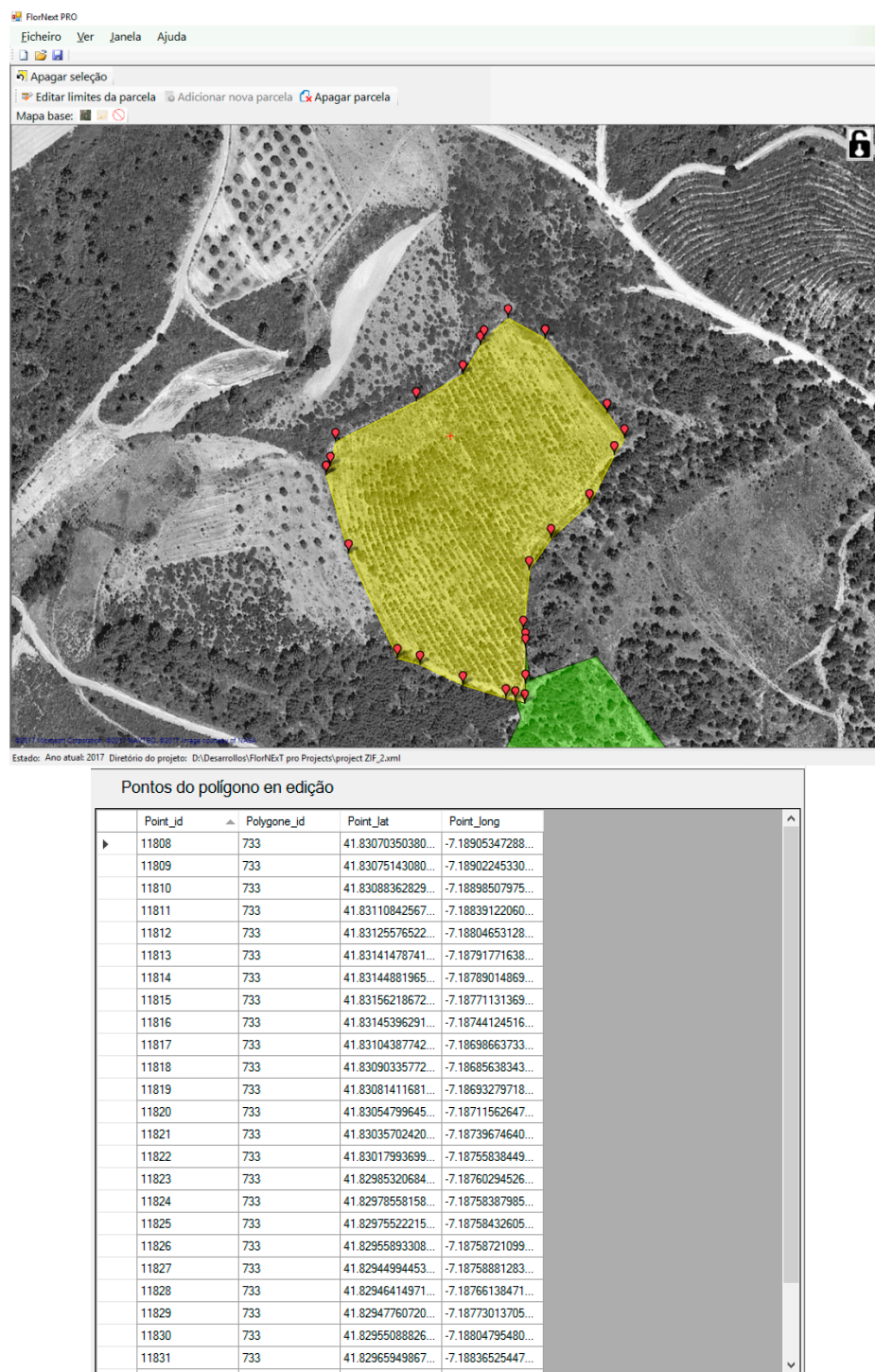
Figure 3. Example of spatial data manipulation capacities in FlorNExT Pro®: polygon editing based on photointerpretation of an aerial photograph in the region showing the location of polygon vertices that can be moved or deleted by the user (**above**) and tabular identification of these vertices (**below**). Translation: *Pontos do polígono em edição*—points of the edited polygon.

FlorNExT Pro® explores several criteria of sustainable multifunctional forestry based on indicators computed by the software throughout the optimization process following a multi-objective approach [40]. Inspired in [24], the tool combines the indicators net present value (NPV), volume growth, carbon sequestration, and losses due to fire to, after normalization, search for optimal management solutions meeting these objectives (Figure 4). NPV is a conventional financial indicator

of value or net benefit over a period of time related to an investment allowing converting benefits to current value units. In FlorNExT Pro®, it is calculated as the summation of discount factors over time (calculated based on discount rate and time) for all the stands harvested during the simulations period. Since costs are difficult to measure, we considered only the benefits of harvesting in the calculations based on the price of wood extracted through thinning and felling. Volume growth is an indicator of productivity referring to the average volume accumulated per ha and year. Carbon sequestration is the amount of atmospheric carbon captured by live trees in the forest stand and it is calculated as 0.479 times the standing biomass [41]. Losses due to fire are an indicator of the probability of a stand to be burned and are is calculated considering both a wildfire occurrence probability given by a logistic model based on stand structure and slope [42] and a wildfire ignition model [43]. Both models were established based on data from Portugal and combined as recommended in [42]. Additional criteria and indicators can be added to the tool after modifications in the code.
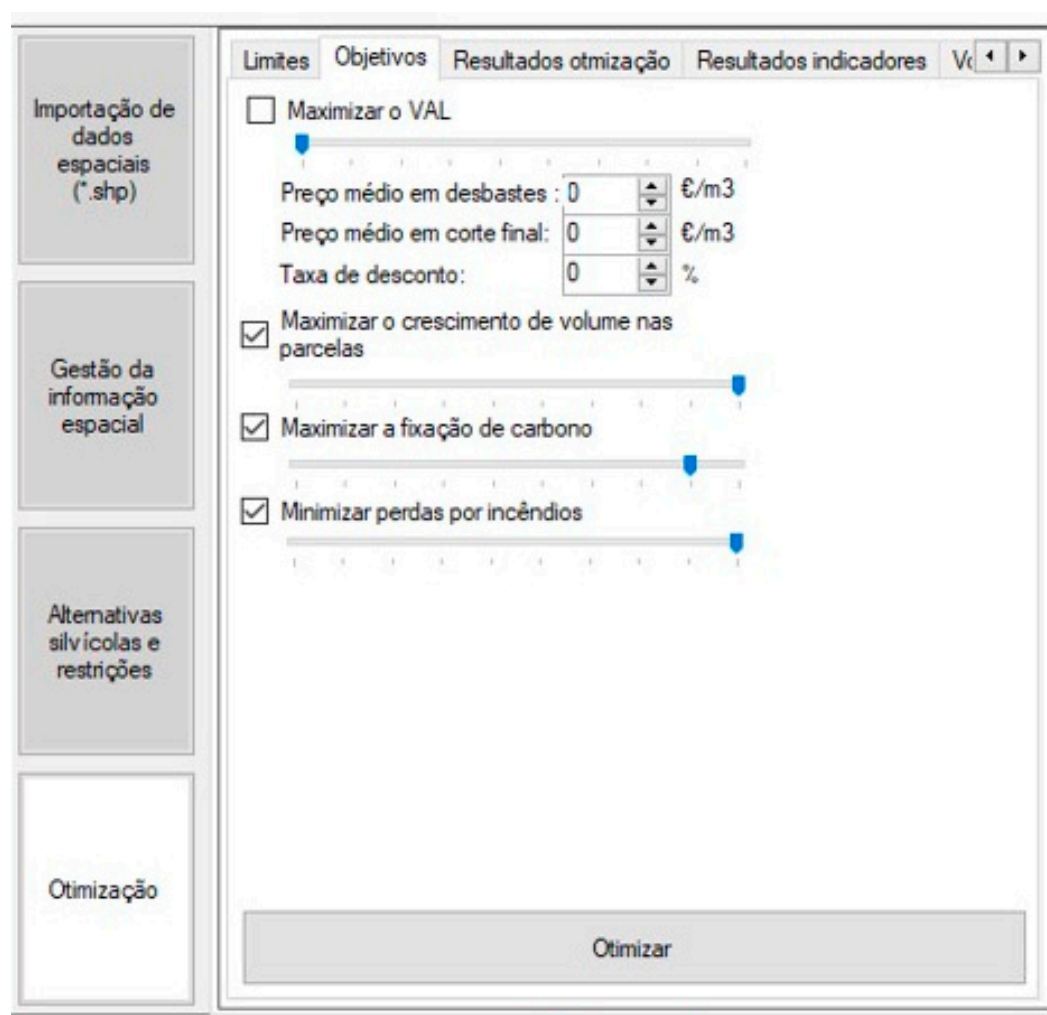

Figure 4. Section of the FlorNExT Pro® interface (in Portuguese) showing the choices of criteria available to be addressed in the multi-objective problem formulation. In this example, the objectives "maximize volume growth in stands", "maximize carbon fixation" and "minimize losses due to fire" have been selected with associated weights of 1, 0.9, and 1, respectively. Translations (in the main folder): *Otimização*—optimization; *Maximizar o VAL*—maximize net present value (NPV); *Preço médio em desbastes*—mean price from thinning; *Preço médio em corte final*—mean price from felling; *Taxa de desconto*—discount rate; *Maximizar o crescimento de volume nas parcelas*—maximize volume growth in stands; *Maximizar a fixação de carbono*—maximize carbon fixation; *Minimizar perdas por incêndios*—minimize losses due to fire.

In the optimization process, following [44], the indicators above were converted into objectives, weighted by scores, and combined in an objective function (1), defined generally as:

$$Max\sum(\lambda_i \cdot \beta_i \cdot W_i \cdot \sum G_i(U_j)) \tag{1}$$

where λ is equal to 1 when objective function $G_i(x)$ is taken into account or 0 when the same objective is not taken into account; β is equal to 1 when a positive value of the objective $G_i(x)$ indicates the best solution or equal to -1 when a negative value is the best solution; W_i is the weight (1–10) given by the user to objective $G_i(x)$; $G_i(x)$ is a normalized objective function G_i; and U_j is the management unit under consideration.

The weight of individual indicators in the optimization process is defined by the user in relative terms using a score of 1–10, providing the opportunity to directly establish forest management plans for an area towards one or several management objectives, from maximization of financial aspects (NPV), production (growth rate), provision of ecosystem services (carbon sequestration), and minimization of risks (fire occurrence).

In addition, constraints such as the total forest area that can be thinned or harvested or the minimum and maximum volume that can be extracted in one single period, can be considered. The definition of objectives and constraints are of the most importance in the linear programming process followed to build the problem for which the solution will be found. In this procedure, all the possible alternatives will be considered. FlorNExT Pro® uses the Branch and Bound [45] procedure to solve iteratively the algebraic problem generated that ends when the minimum value is obtained. Each linear programing problem is a particular problem resulting from choices made by the user on constraints, restrictions, criteria and weights. The user can see the formulation of each individual problem in a file generated by the program (*.lp), also accessible from the "Optimization results" folder in the program's interface. The general structure of FlorNExT Pro® is presented in Figure 5.
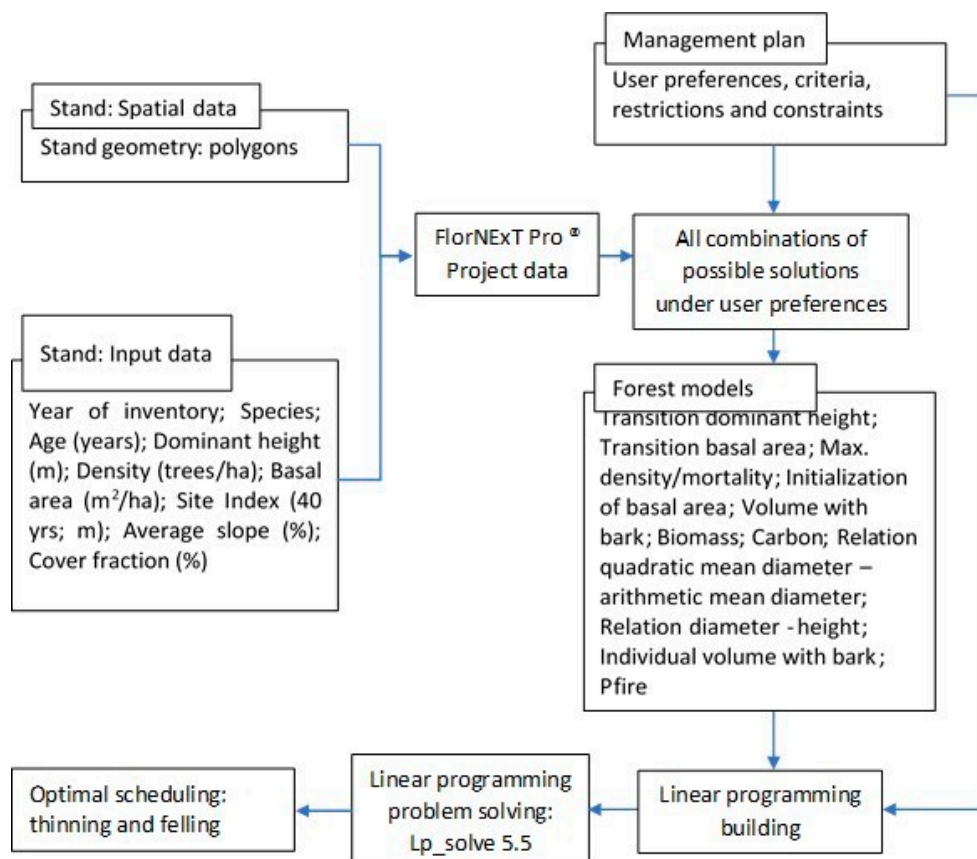

Figure 5. General structure of the forest management optimization tool FlorNExT Pro®.

FlorNExT Pro® was conceived and designed as a transfer tool to support sustainable multi-functional forest management in practice in the northeast of Portugal. The profile of the end-user was therefore fundamental for the definition of the type of product and the capabilities of the tool as well as its graphical interface. Although forest management is directly and indirectly related to several types of actors in different roles (from forest owners to tourists and policy-makers) we conceived FlorNExT Pro® with scientific and technical agents in mind, more specifically forest consultants, and foresters in companies and associations, who have knowledge and skills in forestry and basic knowledge in forest modeling. The development of the tool also involved end-users who participated in meetings in several steps of the process as well as in training sessions.

FlorNExT Pro® was developed in the Visual Studio 2017 Community, with technology. NET Framework 4.5. Programing was done mostly in C# and XML languages. External applications used included GMap.NET.Core (v 1.7.0), open source; GMap.NET.WindowsForms (v 1.7.0), open source; Catfood.Shapefile (v 1.51.0); Microsoft Public License (Ms-PL); and LPSolve (v 5.5) open source. FlorNExT Pro® is a registered Intellectual Property (software) [46] available to download from the web (http://florestasdonordeste.esa.ipb.pt).

2.2. Application

FlorNExT Pro® was applied in a forest area in the Northeast of Portugal with the goal of establishing multi-objective management planning according to different criteria, restrictions and constraints, individually and in combination. Tradeoffs among criteria and indicators of provisioning services (wood extraction) and regulating services (carbon sequestration) were particularly addressed. Climate change mitigation scenarios were foreseen specifically based on the carbon sequestration criterion and indicator, isolated and in combination with others. The study area for this application was comprised of 48 maritime pine stands over a total area of 612 ha. Initial age of the stands (reported to 2016) ranged from 18 to 42 years, tree density from 400 to more than 1600 trees per ha, site index (40 years) from 14 to 20 m, and stand area from 0.6 to 142.4 ha. The study area is part of the Lomba ZIF (Forest Intervention Zone), located in the Vilar de Lomba and São Jumil parishes, Vinhais Municipality, northeast Portugal. The Lomba ZIF is a 2142 ha forest area dominated by maritime pine (*Pinus pinaster*) plantations established in late 20th century. The forest land is owned by multiple private owners and a part of it is communal land. Forest management in the ZIF is of the responsibility of a forest association (Arborea) based on a management plan approved in 2008 at the time of its establishment. This area, including the stands part of the study, is under pressure for thinning and felling from a pellets plant in the neighboring municipality of Chaves which might bias and precipitate management decisions, threatening sustainable forestry. The area is also fire prone given the generally Mediterranean climate with some Atlantic influence (warm-summer Mediterranean climate—Csb) and wildfires occur on a regular basis during summer months.

The application of FlorNExT Pro® consisted in:

- Data gathering and input;
- Definition of management restrictions, constraints and alternatives;
- Optimization; and
- Analysis of outputs.

Spatial data (shapefile) relative to land parcels in the Lomba ZIF was provided by Arborea-Forest Association. Alphanumeric forest inventory data at the stand level was partially collected in 18 plots located in the area and visited in several occasions during 2016. The variables measured in these plots included quadratic mean DBH (cm), dominant height (m), dominant diameter (cm), stand density (live trees/ha), age (years), basal area (m^2/ha), and mean slope (%). Site index (40 years) was estimated for each plot. For the remaining stands, we assigned the variables above based on the comparison of the measured stands and the observed stand condition using aerial photography. Considering the objectives of this work, we assumed as acceptable the error resulting from this process of assigning

stand variables to stands not measured. Data relative to each of the 48 stands considered in this exercise was input in association with the spatial information of each stand.

Restrictions for thinning and felling parameters were established based on silvicultural models for maritime pine in Portugal [47]: Minimum felling age = 35 years; minimum thinning age = 15 years; maximum thinning age = 35 years. Number of days of rain per year (126 days) was based on 30 years observation data for the region. Management alternatives were established considering: number of periods = 10; maximum number of thinnings = 3; interval between operations = 1; starting = 0; and amplitude = 5. This resulted in 1312 unique management alternatives accounted for in the optimization process.

Forest management scenarios were established based on the levels (0 to 10) of the four objectives described above (maximization of NPV, maximization of volume growth, maximization of carbon sequestered and minimization of losses due to fire), summarized in Table 1. The combination of management objectives in scenarios was established to observe the effect of the choice of objectives and weights in the management plans and also expected outcomes of the forest management plan, namely total volume of wood extracted through thinning and harvesting, NPV, carbon sequestered on site and fire risk at the landscape level. For that we summed/averaged indicators calculated throughout the optimization calculations.

The analysis of outputs was performed based on the indicators above, both numerically and visually (graphically). For scenarios maximizing NPV, prices of wood extracted in thinning and harvesting operations were established based on indicative values published by the Portuguese Forest Service (*ICNF*) in 2018 [48]. A discount rate of 2% was considered as adequate to express average interest rates in Portugal in recent years. In some cases other prices of wood and a discount rate of 4% were used to test the sensitivity of the tool.

Table 1. Combinations of management objectives in scenarios tested with FlorNExT Pro® in the Lomba ZIF (Forest Intervention Zone), Portugal. NO: particular objective not considered in the optimization process; YES: particular objective considered in the optimization process. The number within brackets indicates the weight given to objective in the objective function (1–10 scale). * indicates a minimum 2500 m^3 extraction per period (5 years) restriction.

Management Objective	Scenario																											
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20 *	21 *	22 *	23	24	25 *	26	27 *	28
Maximization of NPV	NO	NO	NO	YES (10)	YES (10)	YES (5)	YES (2)	YES (8)	YES (4)	NO	NO	YES (10)	NO	YES (10)	YES (10)	YES (10)	YES (10)	YES (10)	YES (10)	YES (10)	YES (10)	NO	YES (10)	YES (10)	NO	YES (10)	YES (10)	YES (10)
Average wood price (€)																												
—Thinning				15	15	15	15	15	15			15		15	30	30	50	15	15	15	15		50	30		15	15	15
—Felling				26	26	26	26	26	26			26		26	50	50	30	26	26	26	26		30	50		26	26	26
Discount rate (%)				2	2	2	2	2	2			2		2	4	2	2	2	2	2	2		2	2		2	2	2
Maximization of volume growth	NO	NO	YES (10)	YES (10)	NO	YES (5)	YES (2)	YES (8)	YES (4)	YES (10)	NO	NO	YES (10)	NO	YES (10)	YES (10)	YES (10)	YES (10)	YES (10)	YES (10)	NO	NO	NO	NO	NO	NO	YES	YES
Maximization of carbon sequestered	NO	YES (10)	YES (10)	YES (10)	NO	YES (5)	YES (8)	YES (8)	YES (6)	NO	YES (10)	NO	YES (10)	YES (10)	YES (10)	YES (10)	YES (10)	YES (10)	NO	NO	YES (10)	NO	NO	YES (10)	YES (10)	YES (10)	NO	NO
Minimization of losses due to fire	YES (10)	YES (10)	YES (10)	YES (10)	NO	YES (5)	YES (8)	YES (1)	YES (6)	NO	NO	YES (10)	NO	NO	YES (10)	YES (10)	YES (10)	NO	NO	NO	NO	NO	NO	NO	NO	YES (10)	YES (10)	YES (10)

3. Results and Discussion

The application of FlorNExT Pro® in a subset of maritime pine stands in the Lomba ZIF area for individual or combinations of management objectives and weights scenarios (Table 1) resulted in very variable forest management plans. Scenarios targeting one single objective resulted in the highest (lowest in the case minimization objectives) values of the indicator relative to that objective. For example, Scenario 1, minimizing losses due to fire, presented the lowest fire probability (Pfire) among all scenarios tested (Figure 6). The same holds for Scenario 5, targeting maximization of NPV (Figure 7 for comparable prices of wood and discount rate), Scenario 10, targeting maximization of volume growth rate (Figure 8), and Scenario 11, targeting maximization of carbon sequestered (Figure 9). The scenarios combining more than one management objective resulted in solutions that do not maximize or minimize any of the 4 particular objectives but optimize the objective function.

In forestry, the potential amount of wood that can be extracted from the forest is of utmost importance. Therefore, evaluating scenarios based on the extraction of wood is relevant for the sector and important to compare computer-optimized solutions. The maximum volume of wood extracted within the 50-year management period (Figure 6), both through thinning and harvesting (above 300,000 m^3), was obtained for Scenario 14 (maximization of NPV and carbon), Scenario 12 (maximization of NPV and minimization of fire losses), Scenario 26 (maximization of NPV and carbon and minimization of losses due to fire), and Scenario 1 (minimization of losses due to fire). In all these scenarios, extraction of wood took place mainly in a single period at the end of the management period. Scenarios where a 2500 m^3 minimum extraction per 5-year period was imposed were able to perform relatively well in terms of wood extracted. Scenario 21, for example, was similar to Scenario 14 but with this restriction also showed a high volume of wood extracted (295,781 m^3), although with a better distribution of wood extracted throughout time (Figure 10).
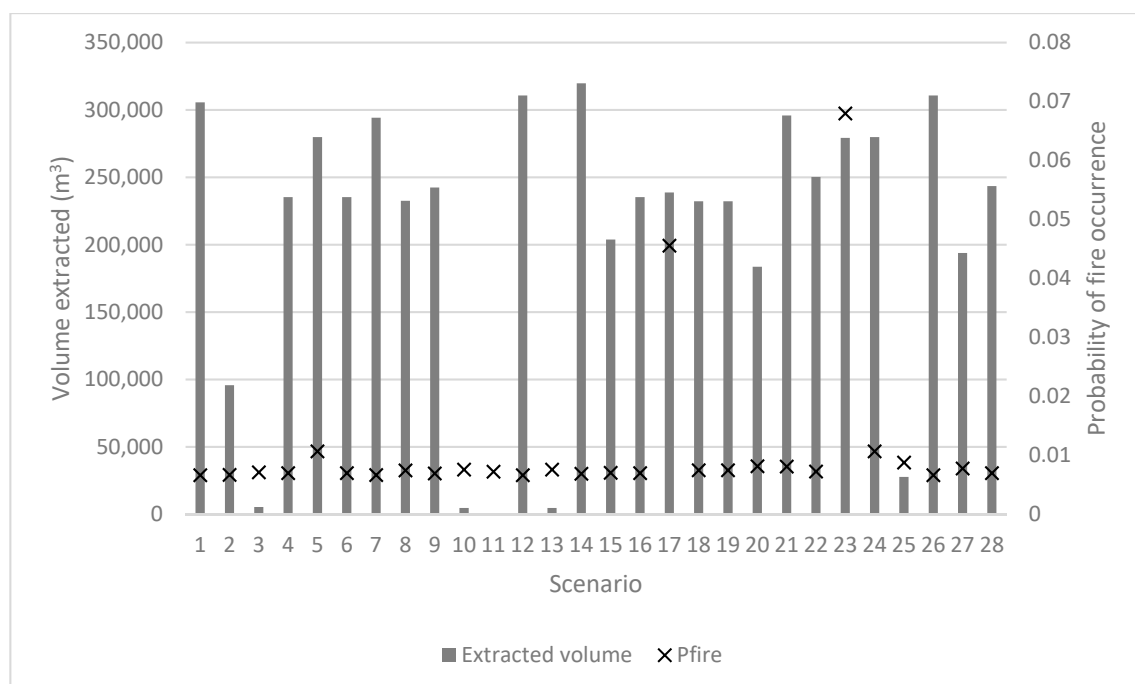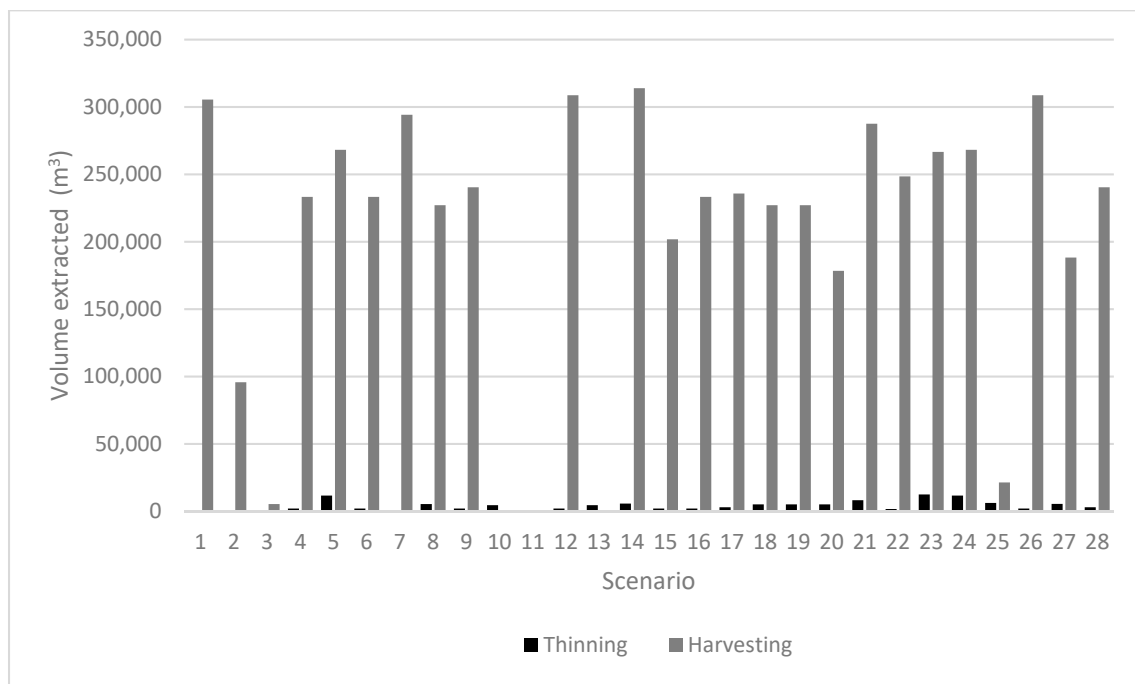

Figure 6. *Cont.*

Figure 6. Volume extracted and average probability of fire occurrence (**top**) and volume extracted by thinning and harvesting (**bottom**) for each of the 28 management objectives scenarios tested in the Lomba ZIF, Portugal.
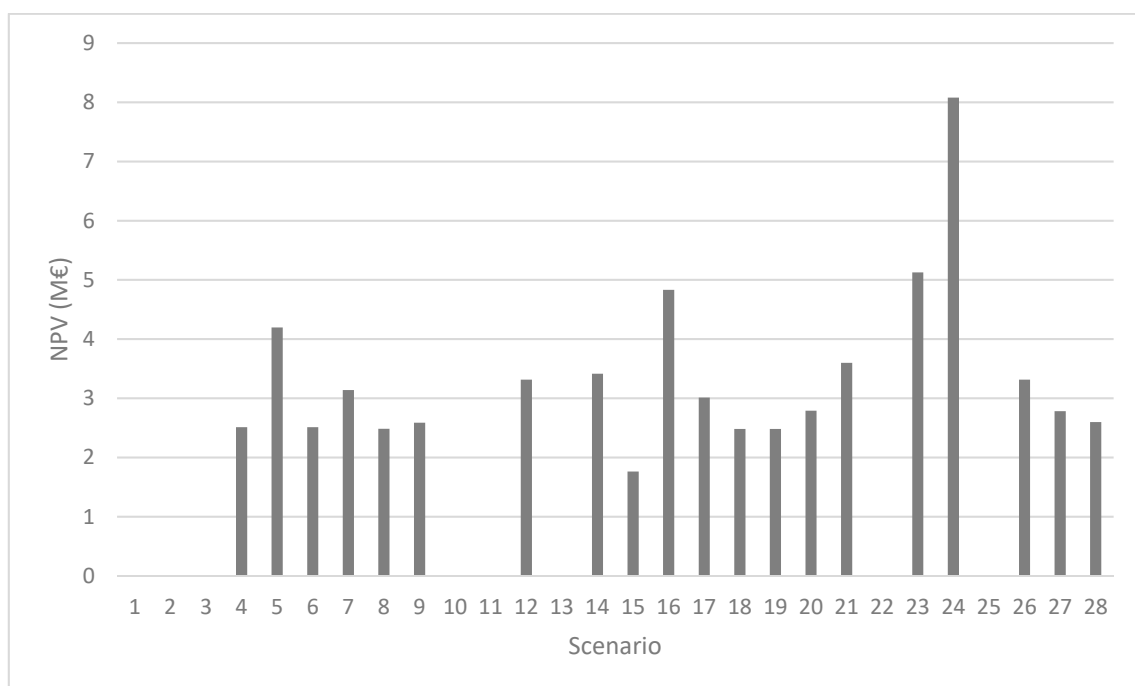

Figure 7. Net present value in million Euro (M€) for maritime pine stands the overall area under management for the 28 management objective scenarios tested in the Lomba ZIF, Portugal.
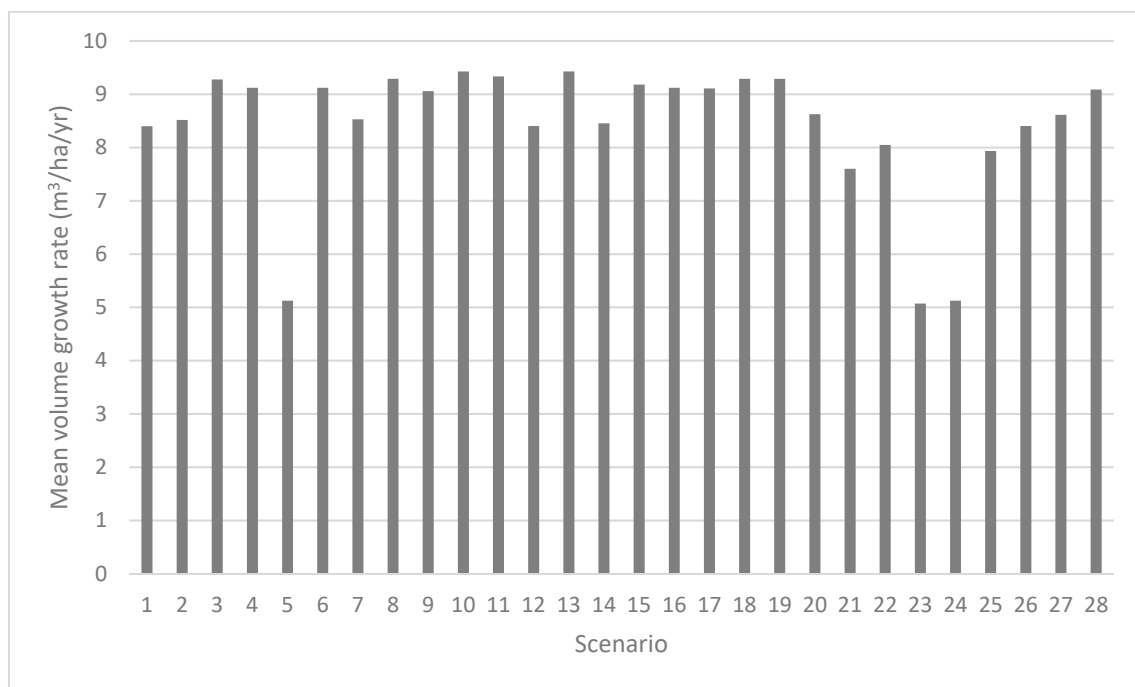
Figure 8. Mean volume growth rate (m^3/ha/year) for maritime pine stands in the overall area under management according to each of the 28 management objective scenarios tested in the Lomba ZIF, Portugal.
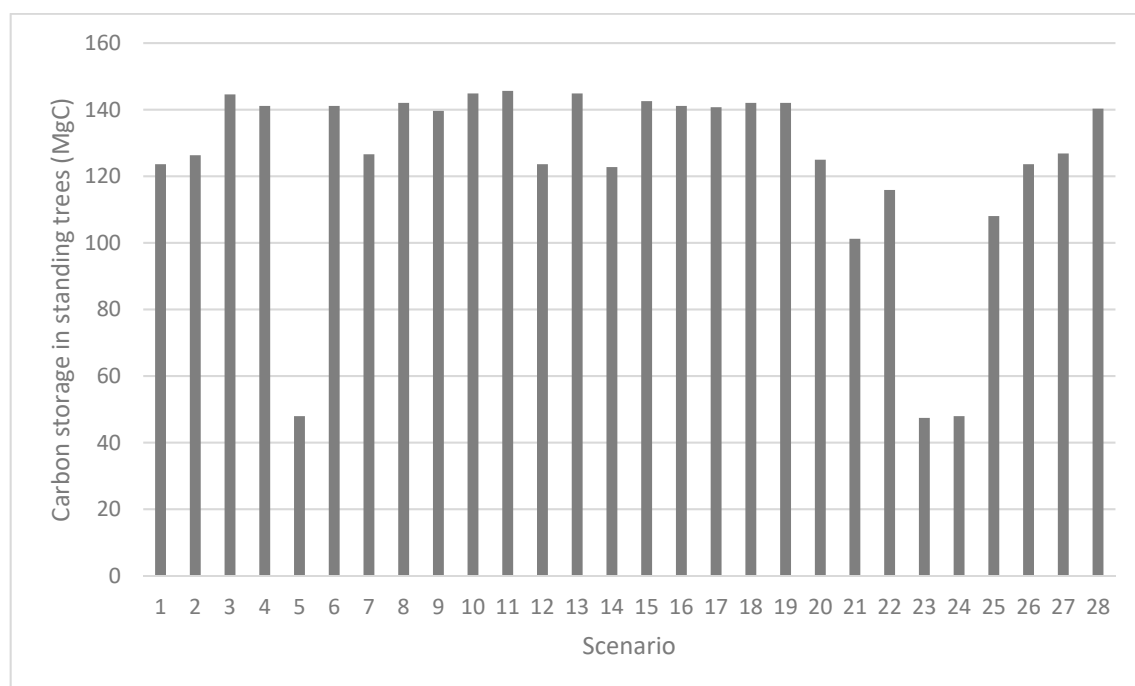

Figure 9. Average carbon storage (Mg) in maritime pine stands in the Lomba ZIF, Portugal, in each of the 28 management objective scenarios tested.
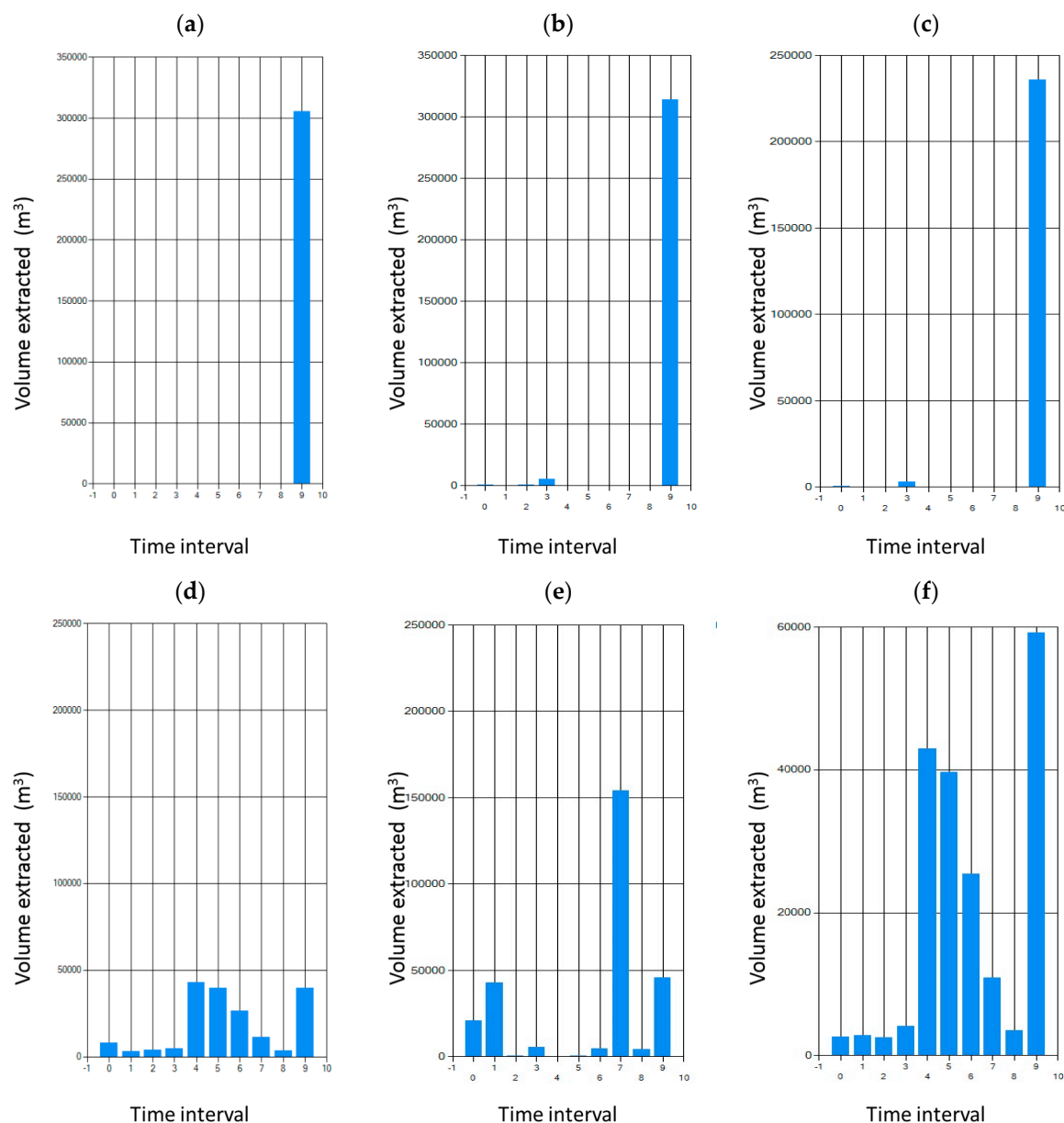
Figure 10. Temporal patterns of wood extraction for contrasting scenarios: (**a**) Scenario 1; (**b**) Scenario 14; (**c**) Scenario 17; (**d**) Scenario 20; (**e**) Scenario 23; and (**f**) Scenario 27. Bars indicate level of extraction in m³ for time intervals 0 to 10.

Scenarios addressing simultaneously the four criteria for the reference prices of wood (Scenarios 4 and 6–9) tended to result in the extraction of considerable amounts of wood (from 232,473 to 294,215 m³), mainly from harvesting (Figure 6), although extraction occurring preponderantly in one single time period (Figure 10). Scenarios under the same conditions but for higher prices of wood or discount rate (Scenarios 15–17) tended to show intermediate to high levels of wood extraction, above 200,000 m³, also with a concentrate temporal pattern of extraction (Figure 10). The scenarios that presented lower levels of wood extraction had only one objective that did not include maximization of NPV (Scenarios 1, 10, 11) or the maximization of growth and carbon sequestered (Scenario 3).

Fire risk (Figure 6) was generally lower in scenarios where minimization of losses due to fire was part of the objective function (Scenarios 1, 2, 4, 6, 7, 9, 12, 23, 26). Scenario 17, however, showed the second highest fire probability. This scenario was established for wood prices higher than the reference prices, in particular wood from thinnings, and addressing all the objectives simultaneously.

Scenario 23 showed the highest Pfire (Figure 6). This scenario targeted only maximization of NPV based on the same prices used in Scenario 17 with a 2500 m^3 minimum extraction. Prices higher than standard for wood coming from thinnings was used to analyze the effect of this factor on the management of the area. Higher fire probabilities can be explained by the fact that the losses due to fire indicator is a function of the G/dg ratio (basal area/quadratic mean diameter) which increases with aging of stands [42]. The scenarios where a minimum extraction of 2500 m^3 per period was imposed (Scenarios 20–22) resulted in a reasonable to high wood extraction level and medium to low Pfire (Figure 6).

The economic indicator used in FlorNExT Pro® provided also useful information for analyzing the alternatives under consideration (Figure 7). Among the scenarios using optimization based on NPV alone or together with other objectives (Scenarios 4–9, 12, 14, 18, 19, 26), Scenario 5 presented the highest average NPV, 4.2 million Euro (M€), followed by Scenario 14 (3.4 M€), and Scenarios 18 and 19 the lowest (2.5 M€). Scenario 24 that showed the highest average NPV (8.1 M€) was established with the objective of maximizing NPV with prices of wood higher than standard prices. The scenarios imposing a minimum extraction of 2500 m^3 per period (Scenario 20 and 21) presented reasonably high values of the indicator (Figure 7).

The scenarios tested also indicated a high variability in terms of the other two indicators. Growth rate (Figure 8) was the highest for scenarios addressing maximization of this indicator, as expected (Scenarios 3, 8, 10, 13). Scenario 11, however, optimized for carbon sequestration only, showed relatively high growth rates (Figure 8). The scenarios with the lowest growth rates were those optimized not taking this indicator into account and correspond usually to scenarios of very low levels of wood extraction (Figure 6). Although growth rates are averages corresponding to forest management optimization where growth was one of the objectives conducting the process in many of the scenarios, the values are apparently higher than expected. According to the 5th National Forest Inventory in the northern region, the mean annual increment (MAI) is only 4.41 m^3/ha/year. As reported in [49], previous inventory data indicate the MAI for the country as usually below 4 m^3/ha/year. However, also based on data from inventory plots, the authors of [50] observed a MAI up to 9.9 m^3/ha/year in higher productivity sites just considering final volume harvested. Values of up to 9.5 m^3/ha/year are also expectable in the center of Portugal (Site Index (50 years) = 21 m) [51].

Carbon storage, representing the average amount of carbon in all stands of the study area during the management periods, showed values that were also relatively high. Considering that in many cases this is due to retention of biomass in stands that become relatively old, the results seem within expected values for live trees of the same species in the Iberian peninsula [52]. The indicator showed that some scenarios favor the storage of higher quantities of carbon than others (Figure 9) in a pattern very similar to that observed for the growth rate indicator. There is, therefore, a strong relationship between these two indicators which might indicate some level of redundancy and a possible bias towards productivity in the optimization process when the two indicators are used together. It can be seen, for example, that the outcomes for Scenarios 10 (maximization of growth) and 11 (maximization of carbon) are similar and that for Scenarios 10 and 13 (maximization of both growth and carbon) they are exactly the same for all the indicators and wood extraction. The same was observed for Scenarios 18 and 19.

The choice of a particular management scenario depends on the objectives established for the management plan and the importance (weight) given to each of them. From a sustainable forestry point of view we tend to favor scenarios for which productivity, contribution to carbon mitigation and the value of wood are balanced but also for which risks (fire) are low. Additionally, an even distribution of felling (and the corresponding revenues) in time can be considered a key factor in forestry where time intervals between periods of income are long. This leads to the scenarios optimizing management for the four objectives considered in FlorNExT Pro®, namely those presented in Table 2. Although all these are optimal solutions, Scenario 27 seems to be a realistic choice considering all the factors above in addition to the prices and discount rate in use. It is the only among these where harvests take

place throughout the management period (Figure 10). Discarding evenness, Scenarios 7 and 9 seem balanced solutions (Table 2). Removing the redundancy between growth and carbon sequestration, i.e., considering the scenarios for three objectives optimized solutions at the bottom of Table 2, any of the solutions seems good and the choice of one depends more on the importance given to the indicators and factors describing these management plan alternatives.

Table 2. Selection of scenarios meeting sustainable forestry goals and associated indicators, wood extraction level and evenness of fellings.

Scenario	Extracted Volume (m^3)	Pfire	NPV (M€)	C (Mg/ha)	Growth (m^3/ha/Year)	Evenness of Harvest Volumes	Wood Prices/Discount Rate
Four objectives **(NPV, growth, C, Pfire)**							
4	235,314.2	0.00697	2.511	141.1	9.121	No	Standard
6	235,314.2	0.00697	2.511	141.1	9.121	No	Standard
7	294,214.6	0.00664	3.138	126.6	8.530	No	Standard
8	232,473.4	0.00742	2.484	142.0	9.288	No	Standard
9	242,438.3	0.00691	2.587	139.6	9.056	No	Standard
27	193,862.4	0.00775	2.781	126.8	8.612	Yes	Standard
15	203,823.8	0.00701	1.761	142.6	9.179	No	Above standard
16	235,314.2	0.00697	4.830	141.1	9.121	No	Above standard
17	238,715.9	0.04554	3.012	140.7	9.108	No	Above standard
Three objectives							
26 (NPV, C, Pfire)	310,697.7	0.00661	3.315	123.6	8.403	No	Standard
28 (NPV, growth, Pfire)	243,418.5	0.00695	2.598	140.3	9.089	No	Standard

Pfire: Probability of fire occurrence; NPV: Net present value.

From stricter optimization perspectives, other alternatives are preferable. Considering fire risk only, for example, a major concern in the south of Europe, Scenario 1 is the best management choice since it presents on average the lowest probability of fire occurrence (Figure 6). In general, this is a good choice considering that besides Pfire, the remaining indicators (Figures 8 and 9) are reasonable, although wood extraction is concentrated in a single period during the simulations.

Considering climate regulation and the importance of forest management for climate mitigation, several scenarios allow the maintenance of large amounts of carbon in live standing trees, near the maximum observed in the study area, such as Scenarios 3, 4, 10, 11, 13, 15–19 and 28. From these scenarios, other factors need to be taken into account in the selection of a particular management plan. The combination of carbon storage with other objectives will increase the amount of wood mobilized in the area and the corresponding revenue. Scenarios 14 and 26, combining carbon sequestration, NPV, and losses due to fire, seem to be good options in this sense, since the amount of wood to be extracted is high and the carbon sequestered is medium to high. At the same time, losses due to fire are low to moderate. FlorNExT Pro® provides not just a friendly way of selecting the best scenarios based on carbon stored in stands but also outputs quantitative data that can be used in the assessment of the supply and value of the climate regulation ecosystem service and its spatial and temporal dynamics in the area of interest. The tool can be combined with others designed with the purpose of assessing ecosystem services, such as InVEST (e.g., [53]), providing forest owners, managers, and policy-makers with a powerful tool, for example, to support schemes for payment of ecosystem services.

Different barriers contribute to low wood mobilization, many of which are related to lack of demand at local and other scales but also to lack of interest from owners, lack of knowledge and tradition, ownership fragmentation and risks and uncertainties. Tools such as FlorNExT Pro® contribute to create knowledge and to promote forest management, particularly based on a multifunctional perspective, tackling several of the barriers above. FlorNExT Pro® is therefore a potential promoter of forest management. Its major attributes (simplicity, accessibility, easiness of use, friendly GIS module) make it particularly appealing for users not familiar with forest modeling or computer programing. The combination of these characteristics with optimization capabilities gives additional attractiveness to the tool. Other tools currently available in Portugal [54]

and other parts of Europe, such as SILVA [55] or BWINPro [56], tend to be more complex and difficult to operate, requiring substantial efforts in modeling and parameterization, and do not have optimization capabilities available directly. FlorNExT Pro® is part of an integrated approach to promote forest modeling tools to support management at several scales based on an online platform (http://florestasdonordeste.esa.ipb.pt/Tools/Index) where several modeling tools are accessible for users in this region. Like in other platforms (e.g., CAPSIS [57]) most tools in this platform are available for modification by the users.

The assessment of carbon sequestration alternatives is one of the most relevant characteristics of FlorNExT Pro® since it provides the means for the calculation of payments of this ecosystem service at the overall landscape scale but also at the level of individual parcels. The fact that the tool addresses fire risk, alone or combined with other objectives, makes it extremely important for creating economic and social opportunities in areas such as the one studied here.

4. Conclusions

FlorNExT Pro® is a versatile, easy to use, and powerful computer tool to support sustainable forestry providing optimized solutions for the management of complex and heterogeneous forest areas. The tool has a series of data (spatial and alphanumeric) management, optimization, and output capabilities that provide the user with the means to implement sustainable forest management addressing maximization of financial (NPV), productive (volume growth rate), and environmental (carbon storage) indicators as well as minimization of risks (fire). FlorNExT Pro® is, therefore, suited to explore the best management scenarios for forest landscapes where different criteria can be of importance. The application of the tool in the northeast of Portugal revealed its potential to find optimized management plans testing a series of scenarios built based on diverse management objectives, costs of wood (thinning and harvest), discount rate, restrictions, and constraints. This application of FlorNExT Pro® also highlighted its usefulness to address the climate regulation ecosystem service through carbon stored in live trees and the probability of fire occurrence, individually or in combination with other indicators.

5. Patents

FlorNExT Pro® has Intellectual Property Rights Registration no. 03/2016/571 (Spain).

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