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Optimization with fire spread simulation for forest management

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Abstract

We propose a method for forest management in which wildfire is modelled explicitly through the integration of optimisation and simulation. Given a forest, the decision problem is to select a plan (i.e. a prescription and a periodicity for shrub cleaning) for each of its stands. Each plan is associated with values for a set of criteria for each period of the temporal horizon. Considered criteria are net present value, biodiversity, carbon stock, and erosion. The problem is modelled by a mixed integer programming (MIP) with the objective of maximizing the net present value and imposing limits for the remaining criteria.

A fire spread simulator, based on shortest path algorithms following the minimum travel time principle, is responsible to identify sets of plans that are not acceptable together as they result in a high rate of fire spread. That information is included in the MIP as constraints. This cycle optimization-simulation is repeated until the plans provided by the MIP are acceptable in all scenarios.

Data from a real landscape case-study has been collected and processed to obtain management and fire parameters required to validate the proposed method, which is being implemented in Python (with Gurobi as a MIP solver, GeoPandas for managing and processing geospatial data, and NetworkX implementation of graph algorithms).

1. Introduction

Forest management problems have been addressed with optimisation techniques for decades as surveyed in Kaya et al. (2016).

We consider the forest management problem of deciding which prescription and shrub cleaning periodicity to apply in each stand. Different variants of this problem have been approached before with mixed integer programming, being harvest scheduling with spatial constraints one of the most studied (for a broader view, see Yoshimoto (2018) for the problem with constraints on clearcut area and Neto (2020) for the problem with habitat fragmentation concerns). Recent works (e.g. Marques et al. 2017) consider, among the net present value, carbon stock and others, fire resistance indicators.

Our main contribution is to explicitly incorporate fire spread simulation in forest management. Optimization is used to select promising plans with respect to forest management indicators (net present value, biodiversity, carbon stock, erosion). Fire spread simulation is used to exclude plans that, taken together, may lead to wildfires with high damage potential.

We consider two modules: an optimization module and a fire spread simulation module. The optimization module, which consists in a mixed integer programming (MIP) model, is responsible for the selection of a global plan, i.e. the calendar of silvicultural operation including shrub cleaning periodicity for each stand, further called prescription, that maximizes the net present value taking into account limits on the biodiversity, carbon stock, soil erosion, standing timber volume, and harvested timber fluctuations between planning periods. The first three limits are imposed to ensure a certain quality of the respective ecosystem services and soil functions. The last constraints aim at maintaining the availability of timber in the forest and simultaneously a stable timber supply.

The fire spread simulation module represents the landscape as a grid network and, using the minimum travel time principle (MTT) (Finney 2002) and an all-pair shortest paths algorithm (Ahuja et al. 1993) allows to obtain the fire paths and fire arrival times at each node of the network for any ignition node. The assessment of the fire potential damage is made by the distance travelled by fire in the quickest path (in a given time interval, i.e. the rate of spread (ROS) of fire is measured in all nodes that have the same fire arrival time) in a set of scenarios.

The interaction between the two models occurs in both directions. The optimization module provides to the simulation module the current plan of each stand. The simulation module generates a set of scenarios that share the fuel model and canopy characteristics derived from the current plan of each stand and have different wind and ignition locations. For each scenario, the fire transmission time between each pair of adjacent nodes is obtained and the ROS is calculated. If the ROS of a fire path is higher than a given threshold, the path is termed unacceptable. The set of stands belonging to an unacceptable path cannot have the current plan because lead to a ROS higher than the acceptance threshold. In that case, a corresponding constraint is inserted in the MIP model. If the simulation module does not identify an unacceptable fire path, the global plan is optimal with respect to all fire scenarios considered.

This paper is organized as follows. In section 2 we detail the optimization module. In section 3, we detail the fire spread simulation module. In section 4, we provide an overview of a landscape being used as a case-study, describe the data gathered, and how the proposed approach is being implemented. In section 5, conclusions are drawn, and extensions are discussed.

2. Optimizing plans

We consider a forest divided into stands. The set of stands is denoted by S. For each stand $s, s \in S$, we represent its area (in ha) with a_s and its set of available plans by P_s.

A plan p, $p \in P_s$, is defined by a prescription and by a brush cleaning periodicity. For example, for an eucalyptus stand, available plans may be characterized by an harvest periodicity (e.g., 10, 11 or 12 years), and a shrub periodicity (e.g, 5, 10 years or never, resulting in nine plans).

We denote by T the set of periods of the planning horizon, being the number of periods of the planning horizon its cardinality $|T|$.

The consequences of applying a plan p to a stand s are measured for each time period, which is indexed by $t, t \in T,$ and are the following:

npv_{sp}^t − net present value (€);
bd_{sp}^t − biodiversity (*index*);
es_{sp}^t − soil erosion (ton);
cb_{sp}^t − stock of carbon (ton) ;
vol_{sp}^t − volume (m^3) of timber removed by thinning and harvest.

For the end of the planning horizon, we define:

$stv_{sp}^{|T|}$ − standing timber volume (m^3).

We consider the following limits that cannot be violated in each period:

b_{min} − biodiversity index;
c_{min} − carbon stock (ton/ha);
e_{max} − soil erosion (ton/ha).

Two further parameters are considered:

stv_s^0 − standing timber volume (m^3) in stand s at the beginning of the first period;
Δ − deviation allowed from the reference volume of timber removed.

The decision variables are:

$$x_{sp} = \begin{cases} 1, \text{if stand } s \text{ is managed with plan } p \\ 0, \text{otherwise} \end{cases}, s \in S, p \in P_s;$$

w − reference level for the volume of removed timber over the planning horizon.

The model is:

$$Max \sum_{s \in S} \sum_{p \in P_s} \sum_{t \in T} npv_{sp}^t x_{sp} \quad (1)$$

$subject\ to$:

$$\sum_{p \in P_s} x_{sp} = 1, s \in S \quad (2)$$

$$\frac{\sum_{s \in S} a_s (\sum_{p \in P_s} bd_{sp}^t \, x_{sp})}{\sum_{s \in S} a_s} \geq b_{min}, t \in T \quad (3)$$

$$\frac{\sum_{s \in S} \sum_{p \in P_s} es_{sp}^t \, x_{sp}}{\sum_{s \in S} a_s} \leq e_{max}, t \in T \quad (4)$$

$$\frac{\sum_{s \in S} \sum_{p \in P_s} cb_{sp}^t \, x_{sp}}{\sum_{s \in S} a_s} \geq c_{min}, t \in T \quad (5)$$

$$\sum_{s \in S} \sum_{p \in P_s} vol_{sp}^t x_{sp} \geq (1 - \Delta) w, t \in T \quad (6)$$

$$\sum_{s \in S} \sum_{p \in P_s} vol_{sp}^t x_{sp} \leq (1 + \Delta) w, t \in T \quad (7)$$

$$\sum_{s \in S} \sum_{p \in P_s} stv_{sp}^{|T|} x_{sp} \geq \sum_{s} stv_s^0 \quad (8)$$

$$x_{sp} \in \{0,1\}, s \in S, p \in P_s \quad (9)$$

$$w \geq 0 \quad (10)$$

The objective function (1) states the management objective of maximizing the net present value. Constraints (2) state that each stand is managed with one and only one prescription and shrub cleaning periodicity, i.e. one plan. Constraints (3) ensures a minimumfor the average biodiversity index value of the forest for each period. Constraints (4) guarantees a maximum for the average erosion of the forest for each period. Constraints (5) imposes a minimum for the average carbon stockage of the forest for each period. Constraints (6) and (7) impose a limit on the fluctuation of the volume of timber removed in each period in relation to a reference value. Constraint (8) states that the volume of standing timber of the forest at period T is greater than or equal to that at the beginning of the first period. Constraints (9) and (10) define the domain of the decision variables.

After the optimization of the model just introduced, a global plan is obtained. This plan is provided to the fire spread simulation which is responsible to identify stands belonging to unacceptable paths. Let U represent the stands belonging to an unacceptable fire path, and, with a slight abuse of notation for clarity, $s\bar{p}$ represent stand s and its current plan, $\bar{p}$. Constraint (11) excludes the use of the current plans of the stands in U together:

$$\sum_{s \in U} x_{s\bar{p}} \leq |U| - 1 \quad (11)$$

At a given iteration, the MIP model to optimize is (1-10) plus the set of all constraints (11) identified in the previous iterations.

Feasibility issues may arise in the first MIP if the limits are too narrow or the plans are not suited. After the insertion of constraints on unacceptable paths, the MIP may become infeasible – meaning that no global plan respecting the unacceptable path criterion can be found. In that case, the identification of the path may be used to drive other fire related measures (e.g. implement fire barriers).

3. Simulating fire spread

Fire spread simulation is based on the minimum travel time principle (MTT) (Finney 2002) which states that fire arrival time at any location is given by the duration of quickest path from the ignition to the location.

We define a grid network representing the landscape. Nodes are associated with locations and arcs are associated with potential fire transmission between adjacent locations. Each arc has a fire transmission time, which depends on the slope, wind and fuel model. The set of transmission times, together with one ignition location, defines a scenario for which the quickest path in a given period is identified.

After the optimization module obtains a global plan, i.e. as a set of plans, a set of fire scenarios is considered. The slope and fuel moisture are the same for all scenarios. For each period, the fuel model and canopy measures are constant (given by the plan selected for each stand). Different transmission times are obtained by varying the wind. For a given set of transmission times, all-pairs quickest paths are determined efficiently. Based on those transmission times, for each potential ignition location, the quickest fire path (in a given period, with a minimum length) is identified and checked against a pre-defined threshold. If the ROS of the fire path is greater then the fire path is unacceptable, and its plans and the corresponding stands are returned to the optimization module which will derive the constraints as (11).

4. Implementation and case-study

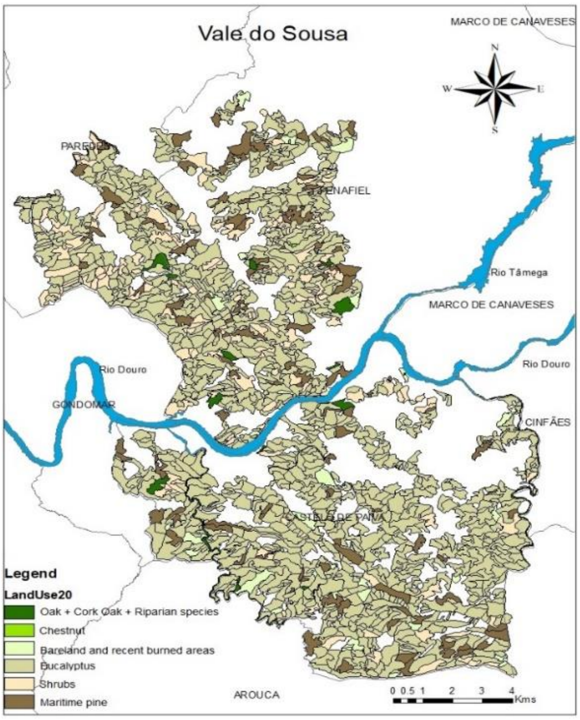

Figure 1 – Case study area location and land occupation in 2020.

The proposed approach is being implemented and validated with data from the Zona de Intervenção Florestal (ZIF) Paiva and Entre-Douro e Sousa in Portugal.

ZIF is a forested landscape located in Northwest Portugal, 100 Km from Oporto. The Associação Florestal do Vale do Sousa, a forest owners association, is the entity responsible for developing the management plan for the whole area. ZIF is divided in 1406 stands with a total area of 14313 *ha*. Data required for the approach was collected and estimated as follows.

The wSADfLOR decision support toolbox was used to automate data processing (Marto et al., 2019). The prescription writer and simulation modules were used to generate the prescriptions and their outputs according to the management planning criteria (Table 1). We also computed several ecosystem services provided by the forested landscape (Barreiro et al 2016, Botequim et al 2021, Marques et al 2021, Rodrigues et al 2021). We considered a planning horizon extending over ten years, with a period corresponding to one year.

A fuel model for each stand from the set of national fuels models proposed in (Cruz and Fernandes 2008, Fernandes and Loureiro 2021) was identified and assigned to each prescription each year of the planning horizon

Table 1- Silvicultural models characteristics and growth models used in simulation.

Species	Stand	Density (trees/ha)	Beat up (%)	Pruning and thinning (year)	Wilson factor	Harvest (year)
***Pinus pinaster* Ait.**	Mixed Pure	1100 1100	15 15	10[1], 25 to 45 (every 10)	0.27	35 to 50
***Eucalyptus* sp. Labill**	Mixed Pure	1400 1400	15 15	3[2] 3[2]	-	10 to 12
***Castanea sativa* Mill.**	Pure	1250	20	According to site index	-	40 to 55
***Quercus robur* L.**	Pure	1600	20	20, 23[3], 27, 37, 45	0.20	40 to 60
***Quercus suber* L.**	Pure	833	20	15, 30, 40, 58, 76	-	30, 40, then every 9[4]
Riparian sp.	Pure	4000	-	-	-	-

[1]Pre-commercial thinning; [2]Stool thinning in 2nd and 3rd coppice cycles, with 1.6 intensity; [3]Prunning; [4]Debarking (cork extraction).

Examples of three attributes of the landscape are given in Figure 2 (altitude, fuel models, and canopy cover).

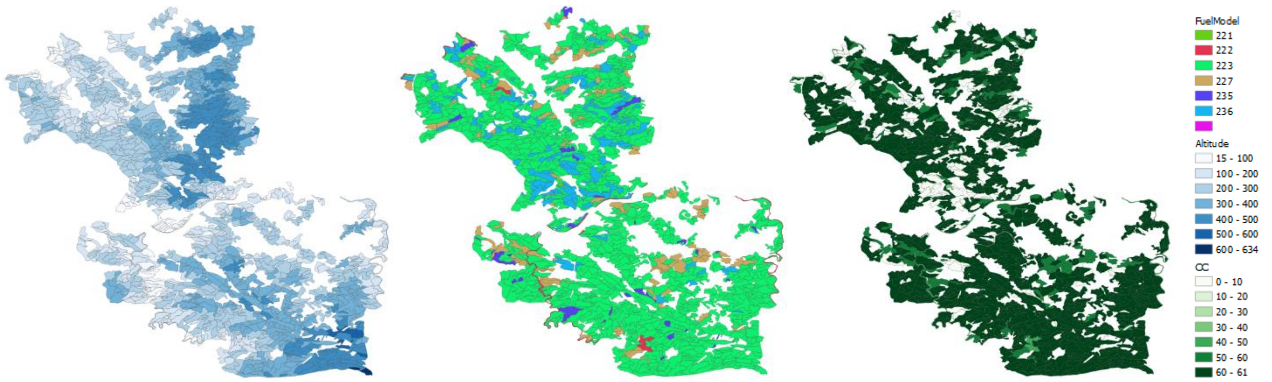

Figure 2- Altitude (600 meters amplitude), fuel models and canopy cover for ZIF.

Geographical information is processed and managed with GeoPandas, Transmission times are calculated with the Rothermel model (with R_0 obtained with BehavePlus6 for each portuguese fuel model and following Andrews (2018) to derive the slope and wind factors in any direction), NetworkX is used for shortest path calculations and visualization, and Gurobi / Gurobipy is used for optimization.

5. Conclusions

We proposed a method for fire-aware forest management based on the interaction of optimization and simulation. Optimization suggests plans respecting limits for different criteria (e.g. biodiversity) and maximizing the net present value, while simulation asserts the plans are acceptable for a different set of scenarios or identify which plans cannot be selected together. In the latter case, the optimization model is updated taking into account that information and the process is repeated. Short-term future work includes the validation with a case-study.

At the time of writing, most of the parameters required for validating the approach in a real landscape are gathered and an implementation in Python is being conducted.

Extensions of the proposed approach may explore four relevant issues:
i) include fire suppression resources and their optimized positioning (Alvelos 2018, Mendes and Alvelos 2022) in the fire spread model;ii) characterize unacceptable scenarios with other measures (or combinations), e.g, fire perimeter, fire area, and average ROS;

iii) address strategic plans where the planning horizon covers several decades;
iv) consider multiple objectives (in fact, the described model can be seen as the one of an iteration of the

epsilon-constraint method for multi-objective optimization) and additional spatial constraints (e.g. clearcut related).

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