Management of maritime pine forests using Decision Support System: a case study in north Portugal

Adelaide Cerveira[1], Isabel Martins[2], João Bento[3], Artur Mota[4], Teresa Fonseca[5]

[1]LIAAD, INESC-TEC & Univ. of Trás-os-Montes and Alto Douro, Portugal

[2]CMAFcIO & ISA, ULisboa, Portugal

[3]Univ. of Trás-os-Montes and Alto Douro, Portugal

[4]Associação Florestal de Ribeira de Pena, Portugal

[5]Forest Research Centre, ULisboa & Univ. of Trás-os-Montes and Alto Douro, Portugal

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Outline

The problem-Motivation

- Maritime pine (Pinus pinaster Ait.) is the leading forest softwood species in Portugal (23 % of the inland forest cover).
- The traditional forest management procedure:
  - Follows silvicultural guidelines supported by forest density indicators based on the experience and sensitivity of the forest technicians,
  - Does not guarantee the best thinning and clear-cutting scheduling.
- It is important to have an “easy-to-use” tool supported by optimization techniques, to be used by the forest managers in the harvest planning of these forests.

The problem-Motivation

Goal

To develop a sustainable management plan for a forest of maritime pine stand of 1393 ha located in the North of Portugal

$\Downarrow$

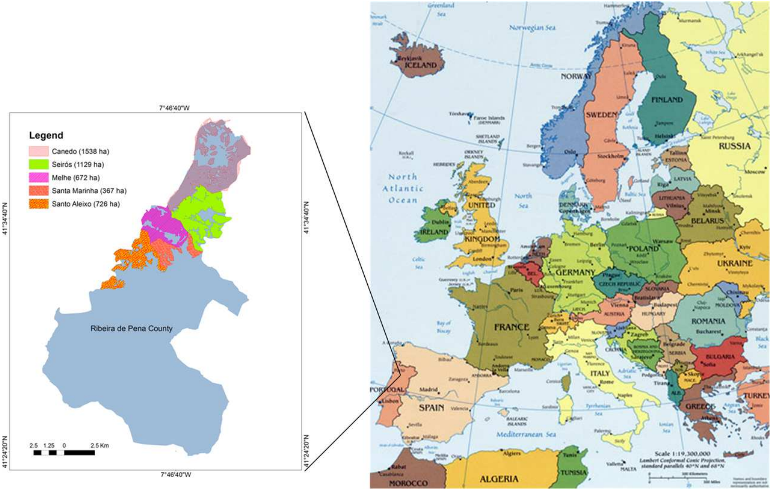
Integer Programming Model

- Objective: maximization of the timber volume obtained by clear-cutting and thinning during the planning horizon (2018-2022);
- Considering Silvicultural, Sustainability, Operational and Spatial constraints.

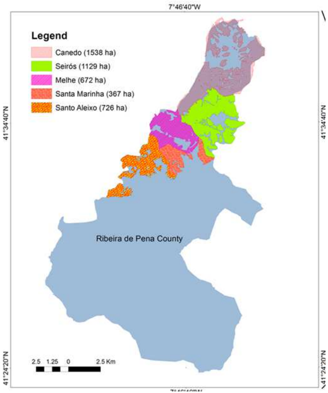
Cerveira, A.; Martins, I.; Mota, A.; Bento, J.; Fonseca, T. *Otimização de planos de exploração florestal em baldios do norte de Portugal*. Rui Carvalho Oliveira José Soeiro Ferreira. Investigação operacional em ação: casos de aplicação. Imprensa da Universidade de Coimbra, 2014, p. 17-56.

Study area

The study area is located in the North of Portugal, in Tâmega's Valley in the Ribeira de Pena county.



Study area



Distributed among five public lands, *baldios*, over 1393 ha

baldios

Are co-managed by the National Forest Services (Autoridade Florestal Nacional, AFN) and the local communities, mostly for timber production. Usually, its management is performed empirically.

Study area

A database based on real data was prepared to support the management planning.

Tree and stand information were collected on forest inventories drawn up from 2004 to 2010

⇒

The stand characteristics were calibrate to 2010 and thereafter projected for 2012, 2013, ...

The simulations were made using forest growth models:

- dominant height growth and site quality models by Marques (1987; 1991),
- stand tables by Moreira e Fonseca (2002)
- basal area growth sub-model of ModisPinaster model (Fonseca, 2004; available in the friendly interface of the CAPSIS platform).

Study area

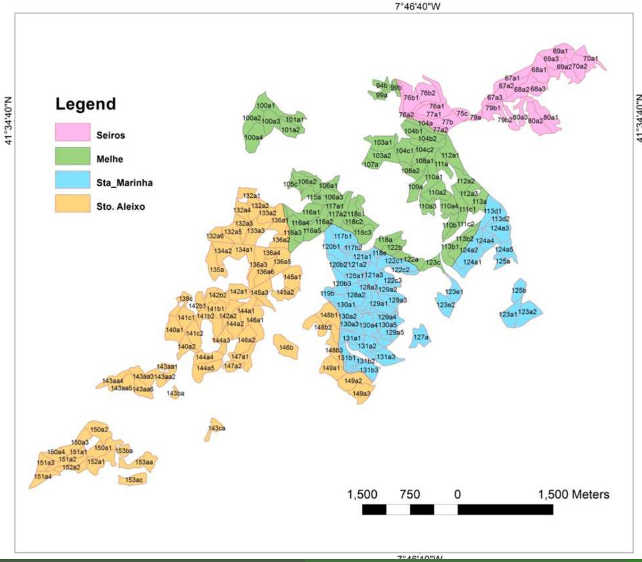
- A **primary delimitation** of the forested area, based on **physical limits**, was provided by the forest technicians from the AFN.
- In each unit a **second division** was made:
  - to assure **homogeneity** of the stands characteristics, such as age and density;
  - to guarantee that the **area** of each **M**anagment **U**nit (MU) **does not exceed 10 ha**.

DATA

209 MUs
(individualized stands,
management units)

Study area- St. Marinha, Melhe, St.Aleixo, Seirós

192 homogeneous stands with area $\leq 10ha$



baldio	area (ha)
St. Marinha	306
Melhe	341
St. Aleixo	465
Seirós	165

Study area- Canedo

17 homogeneous stands with area $\leq 10ha$

baldio	area (ha)
Canedo	121

Study area

Characterization of the baldio's stands in terms of mean area, “area”; stand age, “age”; Stand density Index, “SDI”; volume of standing timber, “*Vp*”, and annual increase of timber production of stands, “*Ac*”, in 2018. ns_i is the number of stands in each baldio.

Baldio	ns_i	area (ha)	age (years)	SDI (%)	Vp (m^3)	Ac ($m^3 ano^{-1}$)
B_1-Sta. Marinha	46	6.5	32.0	26.5	61906	5029
B_2-Melhe	53	6.4	29.0	32.0	70262	6310
B_3-St. Aleixo	68	6.8	32.4	36.4	124391	9544
B_4-Canedo	17	7.1	35.6	43.4	41161	2682
B_5-Seirós	25	6.6	38.5	25.7	29749	2266

Mathematical model

Goal

Obtain a management plan for clearcutting (CC) or thinning (Th) the stands of maritime pine, during the planning period 2018-2022 that maximizes the removed timber volume.

Answer the questions:

- **where** ?
  which stands
- **when** ?
  in which years of the planning horizon interventions should take place and
- **which kind of interventions** ?
  clearcutting or thinning

Mathematical model - Constraints

- **Silvicultural constraints**:
  - Prevent thinning or final cut in stands with no adequate age or density, according to the silviculture of the species:
    - final cut : age $\geq$ 15 yrs,
    - thinning : 15 yrs $\leq$ age $\leq$ 55 yrs;
  - Thinning is mandatory in stands with SDI values $\geq 60\%$;
  - An interval of 5 years between practices;
- **Operational Constraints**:
  - In each removal, the minimum volume (by *baldio*) $= 250m^3$
  - Balanced interventions in each baldio in terms of the removed volume.

Mathematical model- Constraints

- **Organizational Constraints**:
  - Balanced distribution of returns of the entire forest, during the period;
  - By baldio, assure incomes every 3-years period, to avoid conflits among the local communities;
- **Sustainability Constraints**:
  Aim to prevent a compromising removal of timber over the planning horizon.
  - the annual increase of timber production in the last year cannot be less than this value at the beginning of the first year
  - the volume of standing timber in the last year cannot be less than this value at the beginning of the first year

Mathematical model- Constraints

- **Environmental/spatial constraints**: Impose a limit in clearcut area and an exclusion time
  - Impose a **limit in clearcut area**, $A_{max} = 10ha$, imposed by AFN.
  - The exclusion time is **3 years**, *i.e.*, a minimum passage of 3 years before adjacent stands could be harvested.

3 years : is the average time that the species need to have established seedlings from natural regeneration, with average heights of 20-30 cm, after a clear-cut.

Motivation

- To reduce the effect on soil erosion;
- To reduce the risk of tree damages by the wind;
- To reduce a negative impact on wildlife.

Clearcut: is a continuous region with small trees or treeless.

Problem definition - sets

$T = \{1, 2, 3, 4, 5\}$ set of periods

V set of 209 stands

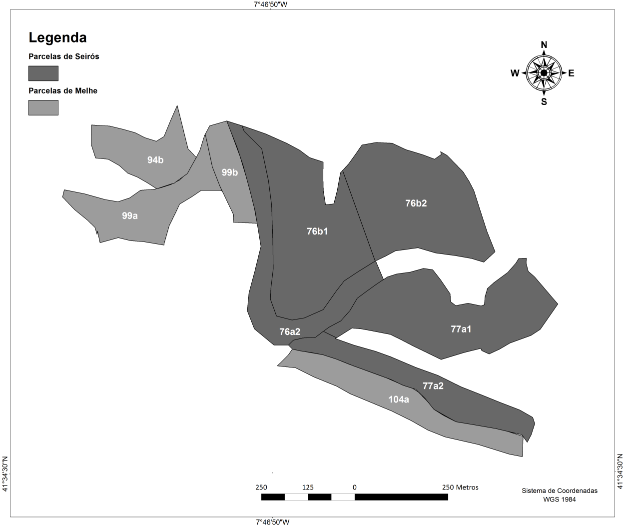
$B = \{B_1, B_2, B_3, B_4, B_5\}$ set of *baldios*

$ns_i \in N$ the number of set of stands in *baldio i*

$\mathcal{R}$ *the set of all possible clusters (group of stands) that cannot be harvested as a whole (with area greater than* $A_{max} = 10$*) and which are minimal, i.e., do not contain any similar cluster.*

Path formulation *(Martins et al. 1999, McDill et al. 2002, Murray e Weintraub 2002, Crowe et al. 2003, Tóth et al. 2013)*

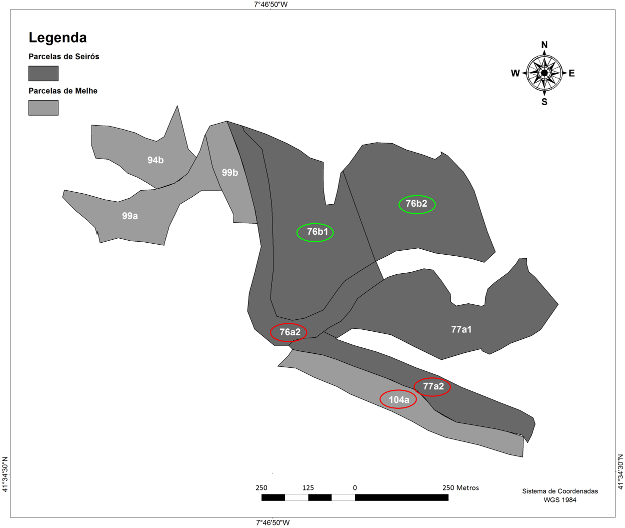
Problem definition - sets



stand	area (ha)
76a2	4.88
76b1	9.23
76b2	8.93
77a1	8.81
77a2	4.34
94b	3.13
99a	4.04
99b	1.92
104a	4.24

$$\mathcal{R} = \{\{76a2, 76b1\}, \{76a2, 77a1\}, \{76b1, 76b2\}, \{77a1, 77a2\}, \{76a2, 99a, 99b\}, \{76a2, 77a2, 99b\}, \{76a2, 77a2, 104a\}\}$$

Problem definition - sets



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Problem definition - parameters

C_j^t - volume obtained by clear-cutting stand j in period t (m^3),

D_j^t - volume obtained by thinning stand j in period t (m^3),

VP_j^t - volume of standing timber in stand j in the last period if a thinning is performed in period t (m^3),

ACD_j^t - annual increase of timber production in stand j in the last period if it is thinned in period t ($m^3 year^{-1}$),

AC_j^1 and AC_j^5 - annual increase of timber production in stand j in period $t = 1$ and $t = 5$ ($m^3 year^{-1}$),

A_j - area of stand j (ha)

I_j - initial age of stand j (i.e., the age of stand j in period $t = 1$)

SDI_j^t : the SDI value of stand j, in period t (in %).

m_i : the maximum volume of timber that can be removed in baldio i.

Decision variables

- clear-cutting variables
  x_j^t binary variables. Takes value **1 if** a **clear-cutting** is performed in **stand** j on period **period** t, and 0 **otherwise.**

- thinning variables
  z_j^t binary variables. Takes value **1 if** a **thinning** is performed in **stand** j on period **period** t, and 0 **otherwise.**

- intervention variables
  y_i^t binary variables. Takes value **1 if** a **thinning** or **clear-cutting** is performed in **baldio** i on **period** t, and 0 **otherwise.**

- bound volume
  $w_i \geq 0$ is an **upper-bound** on the removed volume in baldio i in every period

Mathematical Model- formulation A

$$\max \quad \sum_{t\in T}\sum_{i\in B}\sum_{j\in B_i}\left(C_j^t x_j^t + D_j^t z_j^t\right)$$

subject to :

$$\sum_{t\in T}\left(x_j^t + z_j^t\right) \leq 1, \qquad j \in V,$$

$$y_i^t \leq \sum_{j\in B_i}\left(x_j^t + z_j^t\right) \leq M y_i^t, \qquad i \in B, t \in T$$

$$\sum_{t'=t}^{t+2} y_i^t \geq 1, \qquad i \in B, t \in T$$

$M = ? \quad |B_i|$

Mathematical Model- formulation A

$$\sum_{j\in B_i}\left(C_j^t x_j^t + D_j^t z_j^t\right) \geq 250 y_i^t, \qquad i \in B, t \in T$$

$$\sum_{j\in B_i}\left(C_j^t x_j^t + D_j^t z_j^t\right) \leq w_i, \qquad t \in T, i \in B$$

$$w_i \leq (1+\Omega)\sum_{j\in B_i}\left(C_j^t x_j^t + D_j^t z_j^t\right) + m_i(1-y_i^t), \qquad t \in T, i \in B$$

parameter
$\Omega \in [0,1] \quad (\Omega = 0.2)$

Mathematical Model- formulation A (cont.)

For $t \in T : t < 5$,

$$\sum_{j \in V} \left(C_j^{t+1} x_j^{t+1} + D_j^{t+1} z_j^{t+1} \right) \geq (1 - \Delta) \sum_{j \in V} \left(C_j^t x_j^t + D_j^t z_j^t \right),$$

$$\sum_{j \in V} \left(C_j^{t+1} x_j^{t+1} + D_j^{t+1} z_j^{t+1} \right) \leq (1 + \Delta) \sum_{j \in V} \left(C_j^t x_j^t + D_j^t z_j^t \right),$$

$$\sum_{j \in V} \sum_{t \in T} Vp_j^t z_j^t + \sum_{j \in V} \left(1 - \sum_{t \in T} \left(x_j^t + z_j^t \right) \right) C_j^5 \geq \sum_{j \in V} C_j^1,$$

$$\sum_{j \in V} \sum_{t \in T} Acd_j^t z_j^t + \sum_{j \in V} \left(1 - \sum_{t \in T} \left(x_j^t + z_j^t \right) \right) AC_j^5 \geq \sum_{j \in V} AC_j^1$$

Mathematical Model- formulation A (cont.)

Let t_j^1 the first period $t \in T$ for which the stand j reaches $SDI \geq 60\%$, *i.e.*, $t_j^1 = \min\left\{t \in T : SDI_j^t \geq 60\right\}$

$$\sum_{t \leq t_j^1 + 1} \left(x_j^t + z_j^t\right) = 1, \qquad j \in V : t_j^1 < 5,$$

$$\sum_{t \leq 5} \left(x_j^t + z_j^t\right) = 1, \qquad j \in V : t_j^1 = 5,$$

$$\sum_{t'=t}^{t+2} \sum_{j \in R} x_j^t \leq |R| - 1, \qquad R \in \mathcal{R}, t = 1, 2, 3,$$

Mathematical Model- formulation A (cont.)

$$x_j^t = 0, \qquad j \in V, t \in T : I_j + t < 16,$$

$$z_j^t = 0, \qquad j \in V, t \in T : I_j + t < 16$$

$$\text{or } I_j + t > 56 \text{ or } SDI_j^t < 60,$$

$$x_j^t, z_j^t \in \{0, 1\}, \qquad j \in V, t \in T,$$

$$y_i^t \in \{0, 1\}, \qquad i \in B, t \in T,$$

$$w_i \geq 0 \qquad i \in B$$

Mathematical Model- formulation B

FA-formulation

Does not prevent a baldio from being more, or less, favored in relation to other baldios, regarding the volume of timber removed.

FB-formulation

In order to **avoid an unbalanced situation** between baldios concerning this criterion, we propose to **maximize the minimum relative timber production per baldio**.

Approximate the ratios between the volume of timber effectively removed and the maximum volume of timber that can be removed, as much as possible.

Mathematical Model- formulation B (cont.)

Let, for each *baldio* $i \in B$.

$$p_i = \frac{\sum_{j \in B_i} \sum_{t \in T} \left(C_j^t x_j^t + D_j^t z_j^t \right)}{m_i}$$

be the ratio between the volume of timber effectively removed and the maximum volume of timber that can be removed ($m_i \in \mathbb{R}$).

New objective function:

$$\max \ \min \{ p_i \ : \ i \in B \}$$

$$\begin{aligned} \max \quad & p \\ \textit{subject to} \quad & \sum_{j \in B_i} \sum_{t \in T} \left(C_j^t x_j^t + D_j^t z_j^t \right) \geq m_i p, \qquad i \in B \\ & p \geq 0 \end{aligned}$$

Computational Results

- Testes performed on an Intel(R) Core(TM) i7-4750HQ CPU @ 2.00 GHz with 8GB of RAM.
- Software: FICO Xpress 7.6 (Xpress-IVE 1.24.08 64bit, Xpress-Optimizer 28.01.04 and Xpress-Mosel 3.10.0).
- The Branch and Bound was allowed to run 2 hours.

Computational Results

Formulation sizes and computational results related to branch-and-bound

Model	size		Branch-and-Bound		
	# var.	# constr.	time (s)	gap (%)	obj. funct.
FA	2120	1935	76	0.0	48944 m^3
FB	2121	1940	7200	1.07	0.1075 (47022 m^3)

Computational Results

Removed volume (m^3), in the projection period, with **FA formulation**

Baldio	Type interv.	year 2018	2019	2020	2021	2022	Total
B_1	CC	1053	0	0	1101	0	2154
B_2	CC	0	6029	0	0	5272	11301
B_3	CC	6199	0	4054	5928	4898	21079
	Th	0	0	2158	1450	2110	5718
B_4	CC	0	0	3630	0	0	3630
B_5	CC	0	2315	0	2746	0	5062
Total	CC	7252	8344	9842	11225	12280	48944

clearcutting (CC) $\rightarrow$ 88% of the removed volume

Computational Results

Removed volume (m^3), in the projection period, with **FB formulation**

Baldio	Type interv.	year 2018	2019	2020	2021	2022	Total
B_1	CC	2791	0	3182	3009	0	8981
B_2	CC	3702	3690	0	0	3132	10524
B_3	CC	0	3545	0	4870	4898	13313
	Th	0	1907	0	1450	1094	4451
B_4	CC	0	0	5803	0	0	5803
B_5	CC	1364	0	0	1191	1394	3949
Total		7857	9142	8985	10520	10518	47022

comparing with FA

3% reduction in the removed volume

Computational Results

Ratios p_i, in both formulations

Baldios	**FA**	**FB**
B_1	0.025	0.106
B_2	0.138	0.108
B_3	0.117	0.109
B_4	0.074	0.118
B_5	0.163	0.108

FA

$p_i \in [0.025, 0.163]$

FB

$p_i \in [0.106, 0.118]$

Computational Results

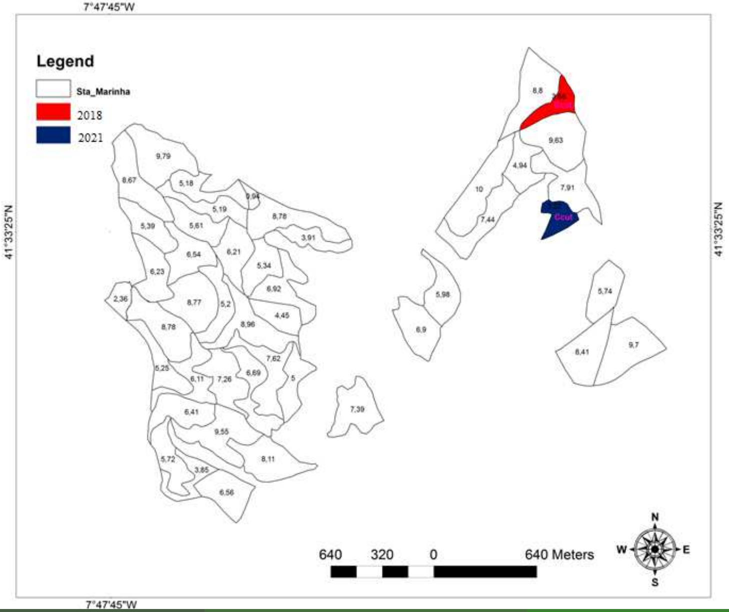
- Thinning occurred only in Baldio B_3 (St. Aleixo).
- Area subject to thinning:
  - **FA** formulation - 43.66 ha (3.1% of the total area)
  - **FB** formulation - 36.4 ha (2.6% of the total area)
- Area subjected to clear-cut:
  - **FA** formulation - 117.21 ha (8.4%)
  - **FB** formulation - 120.6 ha (8.6%)
- Age of the stands subjected to intervention:
  - Thinning - from 25 to 39 years
  - clear-cutting - from 38 to 52 years

Computational Results

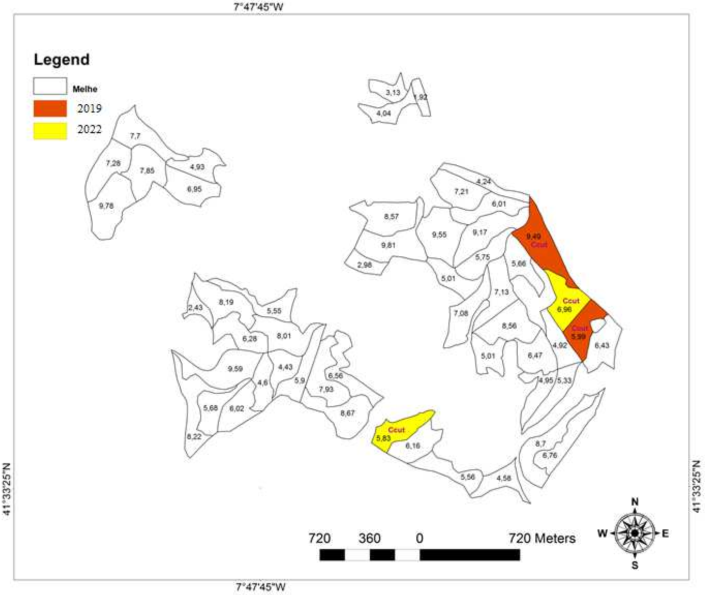
Characterization of *baldios*, $Vp(m^3)$ and $Ac(m^3 ano^{-1})$ in the last year (2022).

Baldio	Initial (2016)		**FA**-formulation		**FB**-formulation	
	Vp	*Ac*	*Vp*	*Ac*	*Vp*	*Ac*
B_1	61906	5029	80999	5511	73273	5121
B_2	70262	6310	84042	6464	84365	6480
B_3	124391	9544	136299	9090	146425	9536
B_4	41161	2682	47674	2656	45247	2527
B_5	29749	2266	31535	2111	32599	2167
Total	327469	25831	380549	25832	381909	25831

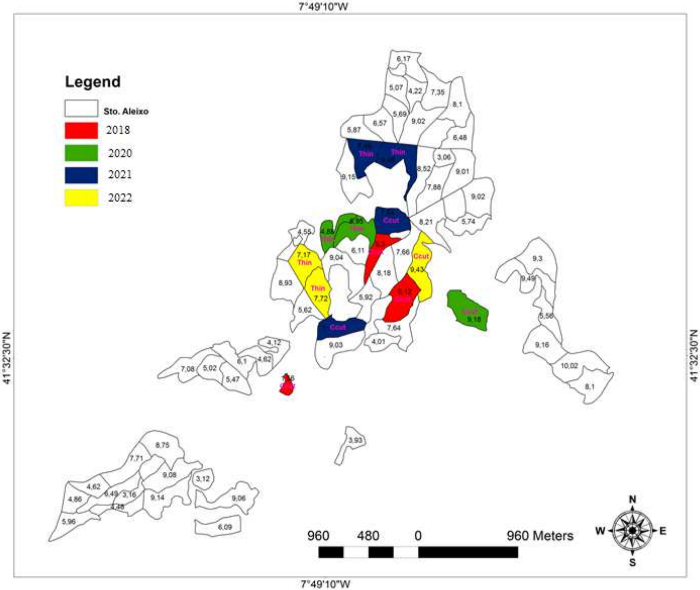
FA-Optimal Solution: B_1-Sta. Marinha



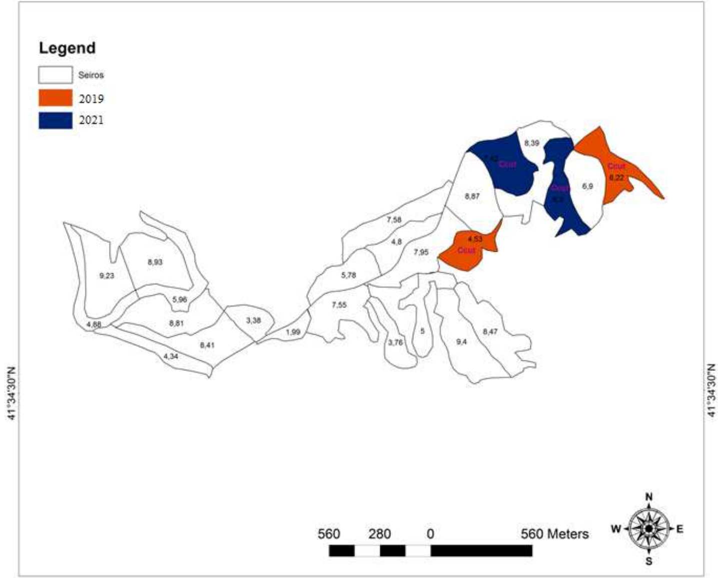
FA-Optimal Solution: B_2-Melhe



FA-Optimal Solution: B_3-St. Aleixo



FA-Optimal Solution: B_5-Seirós



Influence of sustainability constraints.

Model	Intervention volume (m^3)	Intervention area Th (ha)	Intervention area CC (ha)	Characterization - 2022 age (yrs)	Characterization - 2022 Vp (m^3)	Characterization - 2022 Ac ($m^3 ano^{-1}$)
FA	48944	43.7	117.2	32.7	380549	25832
FA $\setminus A_c$	99539	36.5	326.6	27.3	327469	22235
FA $\setminus V_p$	48944	43.7	117.2	32.7	380549	25832
FA $\setminus \{A_c, V_p\}$	301598	14.1	1070.8	9.6	90599	6422

- The annual increase constraints A_c are more effective. With these constraints, the obtained results are equal with or without the standing volume constraints.
- Without both constraints, the amount of removed volume greatly increase.

Conclusions

- Green-up constraints prevent the clear-cut of adjacent MUs according to the Official specifications of a maximum continuous area of 10 ha from clear-cut.
- The management guiding principles translated in this work reveal a careful attitude regarding the extraction of the wood along the planning horizon (due to the sustainability and environmental constraints).
- The annual increase constraints and standing volume constraints ensure sustainable management. The annual increase constraints are the most effective.
- This work constitutes a very useful tool to assist in the elaboration of Forest Management Plans.

Future Research

- To classify the forest into smaller stands, in order to increase management flexibility.
- To include the risk of forest fire.
- To include constraints limiting the minimum stock level of carbon sequestred in the stands.

Obrigada!

Merci !


BIBLIOTECA
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