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Optimal harvest scheduling by blocks

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ABSTRACT

The operations research optimization models are used to generate complex scenarios of forest planning and assisting in decision-making, as they allow evaluating different possibilities of planning. In relation to the different forest activities, the harvesting gets highlighted due to the necessity of simulations that represents logistic issues about the routes building for timber flow for minimize the environmental impacts from the natural resources consumption, as gravel and fossil fuel. In this context, this study aimed to formulate a harvest-scheduling model, wherethe restrictions consisted in reduce the quantity of roads and compare with the traditional model that maximize the volumetric yield. The planning horizon extended over three years and the total area covers 24,000 ha, in which 2,580 ha consisted of*Pinus* spp. and *Eucalyptus* spp. stands, located on state of Paraná, in Southern Brazil.The results obtained showed a reduction of roads on 30% (65 km), maintaining agood yieldwithin the rangeof 5% relative to the totalarea offorest harvesting, proving the model efficiency for resolution of the forest harvesting planning problem based on the transport optimization.

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INTRODUCTION

In the forest harvesting of large areas, which is composed by stands with different ages and for the industrial supply purpose, the cutting plan of management unit's care about the displacement of the cutting front and timber transport, in addition to the environmental impact caused by the activity. This integrated forest vision has gained attention over the years, about the interactions between management units on the establishment of several adjacent harvest areas (Gomide, 2009).

When adding spatial characteristics on the operational research model formulation process it´s necessary to use Mixed Integer Linear Programming (MILP), in order to address the decisions required (Weintraub and Murray, 2006). The integer variables increases the variety of situations where the linear programming models can be applied, as the case of binaries variables (Pizzolato and Gahdolpho, 2009). However, these models should be use cautiously in view of the greater computational requirement (Buongiorno and Gilless, 2003).

Kirby (1975) formulated optimization models involving a connected graph respectively composed by unit managements and roads sections, allowing to relate through restrictions with binary variables the roads sections involved in access of unit managements. Posteriorly, Nelson and Brodie (1990) stratified the forest in harvest blocks and made a planning model of forest-harvesting including restrictions of road construction, obtaining solutions with exact methods and heuristics.

There are many formulated restrictions following the concept of spatial forest planning, such as the adjacency restrictions, classified by Murray (1999) in unit restriction model (URM) and area

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restriction model (ARM). The restrictions ARM are widely studied in forest issues related to harvest blocks creation, as the case of *path algorithm* proposed by McDill et al. (2002), who encouraged the development of new mechanisms to solve this operational problems. Nelson (2001) formulated models comparing the manual creation method of harvesting blocks, through Geographic Information System (GIS), with other forms using computational algorithms, indicating the importance of these studies.

According to Malinovski (2010), the models of forest harvesting that relate the road network involved are important because these affect the production costs. At the same time, the use of adequate road network decreases the environmental degradation, factor of the utmost importance in developing countries where few studies deal with strategic measures for the reduction of the environmental impact (Spinelli and Marchi, 2015).

The objectives of this study were:1) generate aid tools for decision-making on the forest harvest planning in *Eucalyptus* spp. and *Pinus* spp. stands. Optimization models were formulated minimizing the quantity of road sections on forest harvesting and maximizing the harvest volumetric income; 2) simulate forest harvest scenarios from the adoption of minimal harvest ages of *Eucalyptus* spp. and *Pinus* spp. stands, comparing them according to the following performance parameters: harvest area and quantity of road sections.

MATERIAL AND METHODS

Study area:

The data were obtained from a farm that represents a specific situation found in a given Brazilian forest company, located in the state of Parana, southern Brazil. The total planted area covers 23,330 hectares, containing 2,455 management unit of Pinus spp. and Eucalyptus spp. stands. The Table 1 presents the initial structure of the forest stands by age class considering the frequency of Pinus spp. and Eucalyptus spp. on the management units, respectively.

Table 1: Forest initial structure of *Pinus* spp. and *Eucalyptus* spp. stands destined to harvest planning.

Age class (year)	*Pinus*spp.				*Eucalyptus* spp.			
	Area		Management Unit		Area		Management Unit	
	(ha)	(%)	Frequency	(%)	(ha)	(%)	Frequency	(%)
0-4.9	1,497	13.84	110	7.89	9,070	72.53	595	56.13
5-9.9	4,307	39.81	534	38.31	2,866	22.92	335	31.6
10-14.9	2,743	25.35	320	22.96	58	0.46	18	1.7
15-19.9	543	5.02	99	7.03	72	0.58	14	1.32
20-24.9	53	0.49	25	1.79	74	0.59	22	2.08
25-29.9	38	0.35	19	1.36	123	0.98	32	3.02
30-34.9	387	3.58	78	5.6	83	0.66	12	1.13
35-39.9	1,216	11.24	193	13.85	77	0.62	15	1.42
40-44.9	19	0.18	9	0.65	83	0.66	17	1.6
45-49.9	16	0.15	8	0.57	0	0	0	0
Total	10,819	100	1,395	100	12,506	100	1,060	100

The annual production target was 262 and 255 thousand tons of timber for *Eucalyptus* spp. and *Pinus* spp. species, respectively.

Harvest Blocks Generation:

The harvest blocks generation followed a judicious process, due the fact the study area is composed of roads, highways, electricity transmission lines, hydrographic network, preservation areas and management units. Therefore, there are various adjacency criteria to be followed. The interpolation of the information above about the study area composition resulted in the formation of continuous and accessible unit management groups because there isn´t impediment to internal displacement of cutting front and timber transport. Thus, these groups are called harvest blocks.

The used tools were the Geographic Information System (GIS) software of ArcGIS. By the interpolating of the vector information were edited 49 harvest blocks, with average productive area of 550 ha and 45 management units. The Figure 1 is composed by the harvest blocks and roads sections used for the forest production transport from the present study area.

Mathematical Formulation:

The configuration of the forest harvest problem approached requires the formulation of MILP models. The approach used followed the Type I model formulation, as proposed by Johnson and Scheurman (1977). Furthermore, two models were formulated representing two scenarios.

Scenario I was compose by the optimization model where the objective function was maximize the volumetric income of the forest and in Scenario II the objective function was minimize the quantity of retired roads sections by planning period.

All optimization scenarios were simulated with 20% of deviation on the production goal proposed, which was obtained according to preliminary tests. Additionality, it was adopted the minimal harvest ages in which the lower limits were equal to 6 and 12 years old for Pinus spp. and Eucalyptus spp. and Pinus spp., respectively.

It was also necessary to formulate restrictions of blocks integrity to allow a single option of management in each block of harvest.

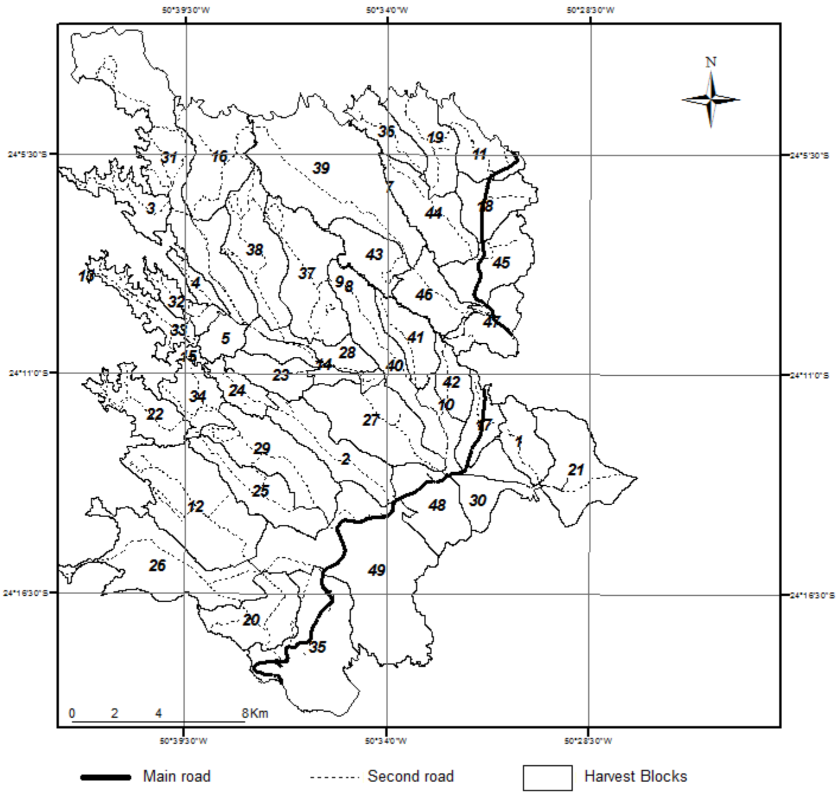

Fig. 1: Map of harvest blocks and road sections from study area.

Using the ArcGIS software, a last set of restrictions was formulated only for the Scenario II, called road access restrictions, that related the stretches of roads required at the time of each harvest block, in order to carry the production to the main roads.

The mathematical formulation structure of Scenario I is given as fallow: (1) objective function to maximize the volumetric yield; (3) blocks integrity restrictions; (4) and (5) volume control restrictions; and (7) binaries variables restrictions. For Scenario II the objective function replaced by the objective function (2) that correspond to minimize the quantity of total road sections, besides the restrictions already presented, the equations group (6) representing the road access restrictions.

$$\text{Maximize Z} = \sum_{i=1}^{B}\sum_{j=1}^{T}(R_{ij}X_{ij}) \qquad (1)$$

$$\text{Minimize Z} = \sum_{i=1}^{B}\sum_{j=1}^{T}(D_{ij}Z_{ij}) \qquad (2)$$

Subjected to: $$\sum_{j=1}^{T} X_{ij} \leq 1 \quad \forall_{i=1\ldots B} \qquad (3)$$

$$\sum_{i=1}^{B}\sum_{j=1}^{T}\sum_{k=1}^{S} V_{ijk}X_{ij} \leq U_b \, \forall_{K=1\ldots S} \qquad (4)$$

$$\sum_{i=1}^{B}\sum_{j=1}^{T}\sum_{k=1}^{S} V_{ijk}X_{ij} \geq L_b \, \forall_{K=1\ldots S} \qquad (5)$$

$$X_{ij} - Z_{ij} = 0 \qquad \forall_{i=1\ldots T}, \forall_{j=1\ldots B} \qquad (6)$$

$$X_{ij}, and Z_{ij} \in \{0,1\} (7)$$

Where:
B = total number of harvest blocks;
T = total number of annual planning periods;
S = total number of products;
Xij = binary decision variable of harvesting the block i on period j;
Rij = volume per hectare of block i on period j;
Zij = binary decision variable of the road section i, period j;
Di = maintenance cost of the road section i on period j.

Vij = total volume of product k on block i and period j.
Ub = lower limit of volumetric production according to the annual demand of each product;
Lb = upper limit of volumetric production according to the annual demand of each product

Resolution and Processing:

The MILP models were constructed using the Microsoft Excel 2013 and processed using CPLEX (IBM-ILOG, 20013) optimization software. The processing performed on a computer with Intel Core i7, processor with 2.6 GHz and 16 GB of RAM.

RESULTS AND DISCUSSION

The difference between the restriction numbers of scenarios is significantly high. Were formulated 215 restrictions in Scenario I, while in Scenario II were formulated 1,300 restrictions, which represented 604% of increase, justified by the inclusion of new spatial component, expressing the relationship of roads access to each harvest blocks on the model contained in Scenario II.

On the models formulated, the adoption of minimum harvest ages allowed generate feasible solutions within 20% of deviations in relation to the production target by period. The adoption of minimal cut ages increased the productivity of harvest blocks (m3. ha-1) in 60% on the moment that delete the young managements units with low stock of harvesting wood. The concept of minimum harvest age is commonly used in spatial planning forestry, in view of works Nelson (2001), Boyland (2004) and Binoti The forest harvesting optimization problems that involve roads construction are complex due to the large number of restrictions involved in the formulation of the models. Andalaft et al. (2002) demonstrate an interesting example, which they considered planning horizons of 2 to 5 years and formulated MILP models with more than 6.000 restrictions related the roads and forest harvesting.

The variation of harvest area (ha) on Scenario I is 4% better than Scenario II, corresponding to 143 ha of difference. On the other hand, for roads sections (km) involved in harvesting, the Scenario I was 30% worse than Scenario II, which represented 65 km of difference. The Table 1 presents the scheduled blocks, total harvest area and total road sections by scenario and planning period.

Table 1: Scheduled blocks, total harvest area and total road sections by scenario and planning period.

	Selected Blocks					
	Scenario I			Scenario II		
	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3
	5	1	11	2	29	1
	12	24	18	8	31	11
	31	25	20	9	32	14
	43	39	23	10	35	16
	49		26	25		20
			35	37		23
			36	39		24
			45	40		26
			46			28
			47			35
						38
Area (ha)	1299	1336.5	1362	1442	1356	1341.5
Roads(km)	95.8	57.4	79.5	69.7	37.3	61.3

In Scenario I was harvested 3,997 ha and the Scenario II it was 4,140 ha. These differences were expected between the two scenarios analyzed due the different objective functions and constraints of formulated in each model. The forest production always was influenced by the restrictions of different natures, as the adjacency restrictions in Castro (2007) and Marianov et al (2004).

Scenario II presented the road network with lower distance, being equal to 168 km, i.e value 27,8% lower than the Scenario I that corresponded in a 65 km of discrepancy. Analyzing the images of the harvest annual dispersion in Figures 3 and 4, it´s possible to notice the visual difference between the Scenarios I and II.

The model formulated in Scenario II was efficient to optimize the forest harvest reducing costs with transport and environmental impacts. These are important aspects as highlighted by Malinovsky (2010), where an average value of R$ 8,231.00 km-1 was obtained for restoring roads with gravel. Besides, Shan et al. (2009) considered the building and restoration of forest roads an important issue due to its high potential environmental impact on the several involved ecosystems.

Conclusions:

The harvested area of Scenario I was 5% less than Scenario II, corresponding to 143 ha of difference. On the other hand, the amount of roads on Scenario II was 30% less than Scenario I, which represented 65 km of difference on the roads network.

The manual creation of blocks using the vetorial information´s permitted to formulate a MILP model according to the real forest harvest problem, integrating decisions about road network maintenance.

With the advancement of technology in hardware and software, further research should focus on computational methods for generation of MILP models to solve problems of forest harvesting minimizing the environmental impact.

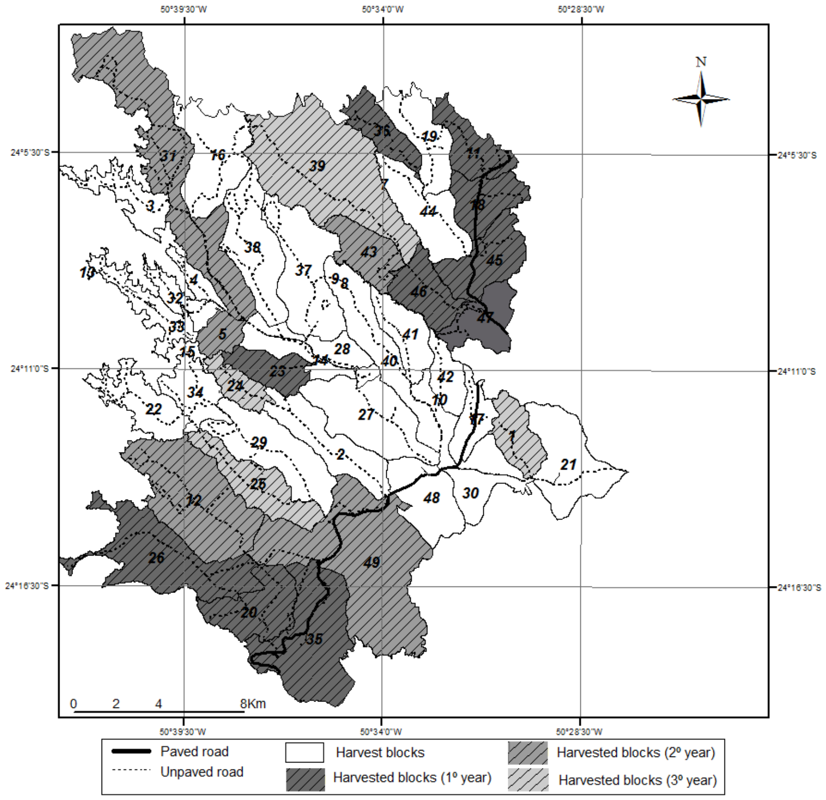

Fig. 2: Result of the harvest dispersion in Scenario I by planning period.

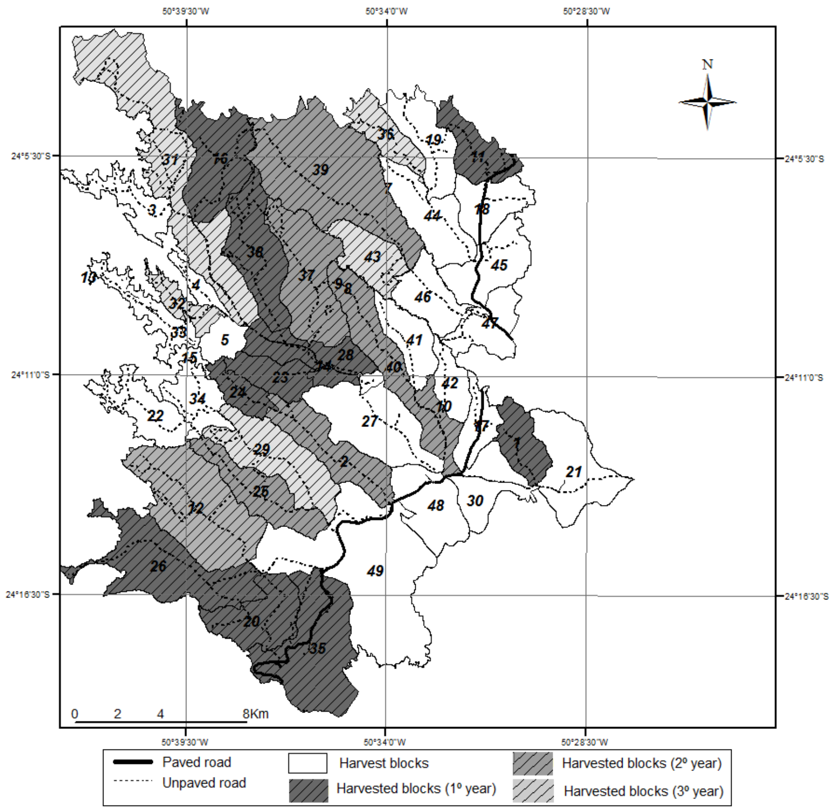

Fig. 3: Result of the harvest dispersion in Scenario II by planning period.

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