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Spatial stratification per district to obtain regulated forest in Brazil

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Abstract
The classic forest regulation model considers the total forest area in order to regulate production to maximize revenue. However, frequently the forest area covers more than one political or socio-economic zoning, such as a district. Taking into account the continuous operation in every one of these zones when optimizing wood harvest and revenue may result in social-economic benefits such as job maintenance and tax collection. Hence, the aim of this study was to assess a regulated forest structure model using the planted area per district as spatial stratification criterion. Three modeling scenarios were established: spatial stratification per district, annual volumetric production per district and the classic total area regulation. All models were formulated under the model 1 of linear programming. An area of 2,191 ha of eucalypt stands, from one to seven years of age, located in three districts in southeastern Brazil, was used to evaluate the proposed scenarios. The optimal solution of the proposed model met the imposed constraints (area, demand and regulation). The stratification per district, under the conditions of the present study, did not reduce net revenue, guaranteed the annual timber supply and resulted in smaller variation in the annual timber volume per district.
Keywords: Forest planning; Linear programming; Social responsibility; Forest management

Introduction

A proper regulation of forest production contributes to the search for sustainability (Leuschner 1990; Davis et al. 2005) and results in the maintenance of a constant annual timber and labor flow. In forest planning models, the production regulation is traditionally imposed as a constraint. This constraint guarantees that, by the end of the planning period, the current structure of the forest age classes is converted in an age structure organized sequentially in time, varying from year one up to the regulatory rotation age (Rodrigues 1997; Davis et al. 2005). In the formulation of this constraint, the total forest area is divided by the number of age classes, resulting in equi-productivity of stands.

However, this approach does not take into account the social and political organization of the areas in which the forest are inserted. For example, most of the Brazilian forestry-based companies run activities in several districts (or municipalities). Therefore, the classical regulation constraint does not guarantee annual timber supply in all districts involved in the investment, as the total forested area is indistinctly considered in the traditional forest regulation model. This may create social implications given that the absence of annual activities in some districts hinders the generation of revenue through tax collection from the forestry activity.

Forestry activities have a strong impact on population and local economy (Bettinger et al. 2009) and stimulating regional development is a demand for complying with forest certification standards. Therefore, the traditional tools for the decision-making process must be adapted to incorporate the social and economic local consequences of the regulation of forest production.

Operations research (OR) techniques have been used in the solution of forest planning problems, such as linear programming (Rodriguez & Lima 1985; Berger et al. 2003; Silva et al. 2003) or metaheuristics; genetic algorithms (Falcão and Borges 2003; Rodrigues et al. 2004a; Silva et al. 2009; Gomide et al. 2009; Binoti 2010); taboo search (Falcon and Borges 2003; Rodrigues et al. 2003) and simulating annealing (Falcon and Borges 2003; Rodrigues et al. 2004b). The use of OR or heuristic tools can assist administrators by theoretically substantiating the decision-making process and setting it against empiricism.

As forest regulation models do not consider annual harvests in different municipalities, incorporating such restrictions in these models can contribute to the generation of continuous income. Although simple, this formulation plays an important practical role by assuring annual harvest activities in all districts where the company operates, which assure the maintenance of economic and social benefits generated by the harvest and related operations. For example, the incorporation of such spatial restriction allows the districts to obtain regular revenue through tax collection and maintain job offer.

Therefore, by incorporating such spatial restriction to the regulation model we assessed (i) whether the spatial stratification per district promotes negative impacts on the net income of the forest enterprise and whether (ii) the optimal solution produced by stratification influences the annual timber supply of the forest company.

This study proposes to modify the classical regulation constraint by using the spatial stratification per district in substitution to the use of the total area. It was used a case study of a forestry enterprise comprising multiple districts to evaluate the forest regulation adopting this method.

Material and methods

Characterization of the hypotheticals Districts

The spatial stratification constraint per district was evaluated considering three hypotheticals districts. For each district stand with age varying from 1 to 7 years was considered. For each age, the respective areas of the forest stand were randomly defined, totalizing 2.191 ha (Table 1). The information on costs, revenues, growth for pure even-aged planted eucalypt stands were obtained from Binoti (2010) and described in more detail later.

Table 1 - Structures of eucalypt stands used in the forest regulation case study in southeastern Brazil

Current age (years)	Stand area (ha)		
	District A	District B	District C
1	73	90	140
2	56	100	120
3	70	80	160
4	77	120	200
5	79	100	100
6	62	80	150
7	73	116	145
Total	490	686	1015

Financial information

Planting and maintenance costs (Table 2) were obtained from Binoti (2010); these costs were converted to American dollars (US$) with a conversion rate of 0.3165 (US$1.00 ≈ R$ 3.15) and the annual cost was showed in table 3. The final forest structure was considered in the calculation of the net present value (NPV). The timber price for the commercial class (with ages equal to or greater than five years) was US$ 25.32/m3 while non-commercial timber (with ages less than five years) was US$ 12.66/m3. The mean harvest cost was US$4.10/m3.

Table 2 - Costs used for the economic evaluation of the regulation models

Year	Activity	Yield (Unit ha^{-1})	Unit	Unit Cost (US$)	Application Area (%)	Total (US$ ha^{-1})
1	Manual fertilization (Limestone)	20.00	mh	4.68	100	93.52
1	Fertilization NPK 06-10-29	13.00	mh	4.55	100	59.18
1	Fertilization NPK 06-30-06	10.00	mh	3.94	100	39.37
1	Field assistent	20.00	mh	3.62	100	72.32
1	Planting row marking	10.00	mh	3.62	100	36.16
1	Manual chemical weed control	11.00	mh	4.61	80	40.54
1	Mechanized chemical weed control	0.95	mh	28.02	20	5.32
1	Sistematic ant control	3.50	mh	3.79	100	13.26
1	Conventional ant control	8.00	mh	3.79	100	30.30
1	Mechanized pit digging	17.00	mh	7.30	80	99.26
1	Water truck irrigation	16.00	mh	5.90	100	94.32
1	Manual cleaning	80.00	mh	3.62	30	86.78
1	Chain saw operator	2.00	mh	8.76	100	17.52
1	Planification	5.00	mh	25.40	0	0.00
1	Planting (with hydrogel)	17.00	mh	5.31	100	90.18
1	Replanting (with hydrogel)	7.00	mh	5.31	100	37.13
1	Manual mowing	30.00	mh	3.62	70	75.93
1	Subsoiling/phosphat e application	1.50	mh	43.08	20	12.92
1	Limestone	1.50	t	19.03	100	28.54
1	Termiticide	0.03	kg	268.30	100	8.05
1	Formicide	8.00	kg	1.36	100	10.84
1	Delivery of seedlings and other inputs	1.00	ha	41.91	100	41.91
1	Hydrogel	3.00	kg	2.12	100	6.37
1	Herbicide	6.00	I	3.03	100	18.15
1	Map fertilizer	0.33	kg	0.43	100	0.14
1	Seedlings	1.20	mil	73.46	100	88.15
1	NPK 06-10-29	0.40	t	301.57	100	120.63
1	NPK 06-30-06	0.12	t	298.32	100	35.80
1	Topography	1.00	ha	20.85	100	20.85
2	NPK 06-10-29 application	13.00	mh	4.55	100	59.18
2	Field assistent	10.00	mh	3.54	100	35.37
2	Manual chemical weed control	15.00	mh	4.61	100	69.10
2	Conventional ant control	6.00	mh	3.79	100	22.72
2	Firebreak manual constuction	200.00	mh	3.62	10	72.32

2	Crowning	16.00	mh	3.62	100	57.85
2	Post-planting manual mowing	16.00	mh	3.62	100	57.85
2	Formicide	7.00	kg	1.36	100	9.49
2	Herbicide	3.00	I	3.03	100	9.08
2	NPK 06-10-29	0.40	t	301.57	100	120.63
3	Manual chemical weed control	13.00	mh	4.61	100	59.88
3	Conventiona ant control	6.00	mh	3.79	100	22.72
3	Firebreak maintenance	200.00	mh	3.79	10	75.75
3	Manual mowing	16.00	mh	3.62	100	57.85
3	Formicide	5.00	kg	1.36	100	6.78
3	Herbicide	6.00	kg	3.03	100	18.15
4	Mechanized chemical weed control	6.00	mh	3.79	100	22.72
4	Formicide	2.00	kg	1.36	100	2.71
5	Mechanized chemical weed control	6.00	mh	3.79	100	22.72
5	Formicide	2.00	kg	1.36	100	2.71
6	Mechanized chemical weed control	6.00	mh	3.79	100	22.72
6	Formicide	2.00	kg	1.36	100	2.71
7	Mechanized chemical weed control	6.00	mh	3.79	100	22.72
7	Formicide	2.00	kg	1.36	100	2.71

mh = man-hour

Table 3 - Planting and maintenance costs used in the economical assessment of the eucalypt stand in in the state of Minas Gerais, southeastern Brazil

Year	Cost (US$ ha^{-1})
0	1,279.56
1	512.03
2	240.41
3	25.36
4	25.36
5	25.36
6	25.36

Source: Binoti (2010).

Yield equation

The data used to estimate the harvest stock were obtained from a continuous forest inventory to fit the logistic model relating wood production to age. The ages ranged from two to seven years, the initial spacing was 3 × 3 m and 2861 observations were used (n = 2,861). The resulting equation is shown below. Equi-productive management units were considered.

$$Volume\left(m^3ha^{-1}\right) = \frac{296.4599}{\left(1 + 19.1454 \times e^{-0.7648 \times Age}\right)}$$

The accuracy of this equation was: bias = -0.2592 m^3 ha^{-1}; residual mean square error (RMSE) = 23.91% and correlation between observed *x* estimated ($r_{y\hat{y}}$) = 0.7761.

Mathematical models

The commonly used constraint for forest production regulation in forest planning models is defined as follows:

$$\sum_{i=1}^{M}\sum_{j=1}^{N} X_{ijk} = \frac{S}{AC} \qquad k = \{1, 2, ..., AC\}$$

In this case, X_{ijk} represents the area of the management unit *i*, under management prescription *j*, whose trees will have *k* periods (years) of age at the end of the planning horizon (PH). The total forest area (S) is divided by the number of age classes (AC) for the regulated forest and there will be a total of AC forest production regulation constraints, one for each age class at the end of PH. The constraint is formulated considering the total number of stand management units (M) and the total number of management alternatives (N).

Since the classical regulation constraint considers only the total forest area, it may occur that, in a determined year of the PH, there is no harvest in each district. In the proposed scenario, a spatial stratification considering the forest area of each district was performed. This approach aims at guaranteeing annual wood harvests in each district and, consequently, contributing to the constant generation of the benefits linked to the harvest and related operations. Mathematically, the constraint is formulated as follows:

$$\sum_{i=1}^{M}\sum_{j=1}^{N} X_{ijpk} = \frac{S_p}{AC} \quad p = \{1, 2, ..., P\} \text{ and } k = \{1, 2, ..., AC\}$$

In which: X_{ijpk} is the management unit area *i*, under prescription management *j*, in each district *p*, whose trees will have *k* periods (years) of age at the end of planning horizon; S_p is the area of forest in each district involved; *P* is the total number of districts involved. Consequently, the number of regulation constraints, in this case, is given by $AC \times P$.

Three regulation scenarios were assessed, whose objective was to maximize the global net income. The net present value (*NPV*) was used as economic criterion:

$$NPV = \sum_{t=0}^{n}\left(R_t - C_t\right)\left(1-\theta\right)^{-t}$$

wherein: C_t = final cost in year *t* (US$); R_t = revenue by end of year *t* (US$); θ = net annual discount rate (%); *n* = number of period of time.

In the Scenario 1, we included the spatial stratification per district in the forest planning model which was formulated based on the "Model I" of linear programming (LP), according to Johnson e Scheurman (1977):

$$MaxZ = \sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{p=1}^{P} C_{ijp} X_{ijp}$$

Subjected to:

$$\sum_{j=1}^{N} X_{ijp} = A_{ip} \quad i = \{1, 2, ..., M\} \text{ e } p = \{1, 2, ..., P\}$$

Area constraint

$$\sum_{i=1}^{M}\sum_{j=1}^{N} V_{ijph} X_{ijp} = V_{ph} \quad h = \{0, 1, \dots, H\text{-}1\}$$ Production constraint per district

$$V_h = \sum_{p=1}^{P} V_{ph}$$

$$V_h > (1-\alpha)D \quad \text{and} \quad V_h < (1+\beta)D$$

$$\sum_{i=1}^{M}\sum_{j=1}^{N} X_{ijpk} = \frac{S_p}{AC} \quad k = \{1, 2, \dots, AC\}$$ spatial stratification constraint per district

$$X_{ijp} \geq 0$$

wherein: C_{ijp} is net present value *(NPV)*, per hectare, of the management unit *i*, under the management prescription *j*, in each district *p*; *M* is the total number of management units (stands); *N* is the total number of management prescriptions; X_{ijp} is the area of the management unit *i*, under the management prescription *j*, in the district *p*; A_{ip} is the total area of the management unit *i*, in each district *p*; V_{ijph} is the volume ($m^3 ha^{-1}$) produced in the management unit *i*, under the prescription *j*, in each district *p*, at the period *h* of the planning horizon; V_{ph} is the total volume ($m^3 ha^{-1}$) produced in each district *p*, in the period *h* of the planning horizon; V_h is the total volume ($m^3 ha^{-1}$) produced in the period *h* of the planning horizon; *H* is the planning horizon; *D* is the annual demand of wood; X_{ijpk} is the area of management unit *i*, under the management prescription *j*, in each district *p*, whose trees will have *k* periods (years) of age by the end of the planning horizon; *Sp* is the forest area in each district; *P* is the total number of district.

In the set of area constraints, there is guarantee of management of the whole management unit area *i*, submitted to the management prescription *j*. The set of production constraints refers to the annual timber production. The total timber volume harvested in each year of the planning horizon *(V_h)* corresponds to the volumes harvested in each district in the same year. This constraint does not establish a limit for the wood volume harvested annually. Therefore, it was associated to an annual wood demand *(D)* of 100.000 m^3. To allow for flexibility in this set of constraints, a variation in the annual production was established. This variation was incorporated into the constraint considering minimum *(α)* and maximum *(β)* values of 20%.

The spatial stratification constraints per district, establishes that, every year, a minimum of volume be harvest in all districts and, after the transition period, a regulated forest be obtained.

In the Scenario 2, the effect of the production restriction per district was assessed. The spatial stratification per district in the Scenario 1 was replaced by the classic regulation constraint. The other constraints were kept the same. The model of linear programming (LP) was defined as:

$$MaxZ = \sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{p=1}^{P} C_{ijp} X_{ijp}$$

Subjected to:

$$\sum_{j=1}^{N} X_{ijp} = A_{ip} \quad i = \{1, 2, ..., M\} \text{ e } p = \{1, 2, ..., P\}$$

Area constraint

$$\sum_{i=1}^{M}\sum_{j=1}^{N} V_{ijph} X_{ijp} = V_{ph} \quad h = \{0, 1, \dots, H\text{-}1\}$$ Production constraint per district

$$V_h = \sum_{p=1}^{P} V_{ph}$$

$$V_h > (1-\alpha)D \quad \text{and} \quad V_h < (1+\beta)D$$

$$\sum_{i=1}^{M}\sum_{j=1}^{N} X_{ijk} = \frac{S}{AC} \quad k = \{1, 2, ..., AC\}$$

$$X_{ijp} \geq 0$$

Wherein S is the total area of the forest. The other terms were defined previously. This constraint imposes forest regulation, considering the total forest area. The regulatory rotation age was five years and the harvest interval was one year. The constraints of area and of annual wood production were the same ones used in the Scenario 1. The minimum *(α)* and maximum *(β)* limits of the desired production and the annual demand were kept the same.

In the Scenario 3, the classic production regulation model was adopted as:

$$MaxZ = \sum_{i=1}^{M}\sum_{j=1}^{N} C_{ij} X_{ij}$$

Subjected to

$$\sum_{j=1}^{N} X_{ij} = A_i \quad i = \{1, 2, \dots, M\}$$

Area constraint

$$\sum_{i=1}^{M}\sum_{j=1}^{N} V_{ijh} X_{ij} = V_h \qquad h = \{0, 1, \ldots, H\text{-}1\}$$

Production constraint

$$V_h > (1-\alpha)D \quad \text{e} \quad V_h < (1+\beta)D$$

$$\sum_{i=1}^{M}\sum_{j=1}^{N} X_{ijk} = \frac{S}{AC} \qquad k = \{1, 2, ..., AC\}$$

Classical regulation constraint

$$X_{ij} \geq 0$$

wherein: C_{ij} is the net present value *(NPV)*, per hectare, of the management unit *i*, under the management prescription *j*; X_{ij} is the area of the management unit *i*, under the management prescription *j*; A_i is the total area of the management unit *i*; V_{ijh} is the volume (m^3 ha^{-1}) produced in the management unit *i*, under the prescription *j*, in the period *h* of the planning horizon; V_h is the total volume (m^3 ha^{-1}) produced in the period *h* of the planning horizon; *D* is the stipulated wood demand; *H* is the planning horizon; X_{ijk} is the area of the management unit *i*, under management prescription *j*, whose trees will have *k* periods (years) of age at end of the planning horizon; *S* is the total forest area; *AC* is the number of age classes for the regulated forest.

The regulatory rotation age for all scenarios was five years with a harvest interval of one year under the clear cut silvicultural system. Short rotations, i.e. around seven years, are predominant in Brazil (IBÁ 2016). Specially to produce charcoal for use by the steel industry, the rotation is commonly five years. Because the data used in this work were provided by the forestry branch of a steel company, we decided to adopt their regulatory rotation age. A planning horizon of eight year was considered. The net annual discount rate was of 8.75% and we considered that the operations were performed at the beginning of each year. Additionally, the minimum harvesting ages of five and maximum of seven years under high forest system were considered. The analyses were performed using Lindo (*Linear, Interactivate, and Discrete Optimizer*), demo version 6.1, 2002 to obtain the optimal model solution for the forest planning.

Results

The problem formulation resulted in 81 decision variables (management prescriptions) according to table 4. The spatial stratification per district (Scenario 1) resulted in greater divisibility of the management units (Table 5), in relation to the other scenarios. The optimal model solution indicated 35 non-null decision variables when considering the spatial stratification per district, whereas in the Scenarios 2 and 3, 27 non null decision variables were generated.

Table 4 - Viable management prescriptions for a planning horizon of eight year

Management Unit	District	Current age (year)	Rotation (year)	Planning horizon 0	1	2	3	4	5	6	7	Final Age (year)	Management prescription
1	1	1	5					■				4	X_{111}
1	1	1	6						■			3	X_{121}
1	1	1	7							■		2	X_{131}
2	1	2	5				■					5	X_{211}
2	1	2	6					■				4	X_{221}
2	1	2	7						■			3	X_{231}
3	1	3	5-5			■					■	1	X_{311}
3	1	3	6				■					5	X_{321}
3	1	3	7					■				4	X_{331}
4	1	4	5-5		■					■		2	X_{411}
4	1	4	5-6		■						■	1	X_{421}
4	1	4	6-5			■					■	1	X_{431}
4	1	4	7				■					5	X_{441}
5	1	5	5-5	■					■			3	X_{511}
5	1	5	5-6	■						■		2	X_{521}
5	1	5	5-7	■							■	1	X_{531}
5	1	5	6-5		■					■		2	X_{541}
5	1	5	6-6		■						■	1	X_{551}
5	1	5	7-5			■					■	1	X_{561}
6	1	6	6-5	■					■			3	X_{611}
6	1	6	6-6	■						■		2	X_{621}
6	1	6	6-7	■							■	1	X_{631}
6	1	6	7-5		■					■		2	X_{641}
6	1	6	7-6		■						■	1	X_{651}
7	1	7	7-5	■					■			3	X_{711}
7	1	7	7-6	■						■		2	X_{721}
7	1	7	7-7	■							■	1	X_{731}
8	2	1	5					■				4	X_{812}
8	2	1	6						■			3	X_{822}
8	2	1	7							■		2	X_{832}
9	2	2	5				■					5	X_{912}
9	2	2	6					■				4	X_{922}
9	2	2	7						■			3	X_{932}
10	2	3	5-5			■					■	1	X_{1012}

10	2	3	6				■					5	X_{1022}
10	2	3	7					■				4	X_{1032}
11	2	4	5-5		■					■		2	X_{1112}
11	2	4	5-6		■						■	1	X_{1122}
11	2	4	6-5			■					■	1	X_{1132}
11	2	4	7				■					5	X_{1142}
12	2	5	5-5	■					■			3	X_{1212}
12	2	5	5-6	■						■		2	X_{1222}
12	2	5	5-7	■							■	1	X_{1232}
12	2	5	6-5		■					■		2	X_{1242}
12	2	5	6-6		■						■	1	X_{1252}
12	2	5	7-5			■					■	1	X_{1262}
13	2	6	6-5	■					■			3	X_{1312}
13	2	6	6-6	■						■		2	X_{1322}
13	2	6	6-7	■							■	1	X_{1332}
13	2	6	7-5		■					■		2	X_{1342}
13	2	6	7-6		■						■	1	X_{1352}
14	2	7	7-5	■					■			3	X_{1412}
14	2	7	7-6	■						■		2	X_{1422}
14	2	7	7-7	■							■	1	X_{1432}
15	3	1	5					■				4	X_{1513}
15	3	1	6						■			3	X_{1523}
15	3	1	7							■		2	X_{1533}
16	3	2	5				■					5	X_{1613}
16	3	2	6					■				4	X_{1623}
16	3	2	7						■			3	X_{1633}
17	3	3	5-5			■					■	1	X_{1713}
17	3	3	6				■					5	X_{1723}
17	3	3	7					■				4	X_{1733}
18	3	4	5-5		■					■		2	X_{1813}
18	3	4	5-6		■						■	1	X_{1823}
18	3	4	6-5			■					■	1	X_{1833}
18	3	4	7				■					5	X_{1843}
19	3	5	5-5	■					■			3	X_{1913}
19	3	5	5-6	■						■		2	X_{1923}
19	3	5	5-7	■							■	1	X_{1933}
19	3	5	6-5		■					■		2	X_{1943}
19	3	5	6-6		■						■	1	X_{1953}
19	3	5	7-5			■					■	1	X_{1963}
20	3	6	6-5	■					■			3	X_{2013}
20	3	6	6-6	■						■		2	X_{2023}
20	3	6	6-7	■							■	1	X_{2033}
20	3	6	7-5		■					■		2	X_{2043}
20	3	6	7-6		■						■	1	X_{2053}
21	3	7	7-5	■					■			3	X_{2113}
21	3	7	7-6	■						■		2	X_{2123}
21	3	7	7-7	■							■	1	X_{2133}

■ Perform harvesting and planting operations.

□ Do not carry out harvesting and planting operations.

Table 5 - Optimal solution obtained of forest regulation models for planted eucalypt forests in southeastern Brazil, considering spatial stratification per district (Scenario 1), annual volumetric production per district (Scenario 2) and classical production regulation (Scenario 3)

Scenario 1		Scenario 2		Scenario 3	
Decision variables	Area (ha)	Decision variables	Area (ha)	Decision variables	Area (ha)
X_{121}	73.0	X_{121}	73.0	X_{121}	73.0
X_{221}	49.0	X_{221}	56.0	X_{221}	56.0
X_{231}	7.0	X_{231}	-	X_{231}	-
X_{321}	21.0	X_{321}	-	X_{321}	-

X_{331}	49.0	X_{331}	70.0	X_{331}	70.0
X_{431}	-	X_{431}	19.5	X_{431}	19.5
X_{441}	77.0	X_{441}	57.5	X_{441}	57.5
X_{551}	-	X_{551}	2.5	X_{551}	-
X_{561}	79.0	X_{561}	76.5	X_{561}	79.0
X_{641}	43.0	X_{641}	62.0	X_{641}	-
X_{651}	19.0	X_{651}	-	X_{651}	62.0
X_{711}	18.0	X_{711}	-	X_{711}	48.1
X_{721}	55.0	X_{721}	73.0	X_{721}	24.9
X_{822}	90.0	X_{822}	90.0	X_{822}	90.0
X_{922}	82.9	X_{922}	12.9	X_{922}	12.9
X_{932}	17.1	X_{932}	87.1	X_{932}	87.1
X_{1022}	25.7	X_{1022}	60.7	X_{1022}	-
X_{1032}	54.3	X_{1032}	19.3	X_{1032}	80.0
X_{1132}	8.5	X_{1132}	-	X_{1132}	-
X_{1142}	111.5	X_{1142}	120.0	X_{1142}	120.0
X_{1242}	2.5	X_{1242}	-	X_{1242}	2.5
X_{1262}	97.5	X_{1262}	100.0	X_{1262}	97.5
X_{1342}	48.8	X_{1342}	-	X_{1342}	
X_{1352}	31.2	X_{1352}	80.0	X_{1352}	80.0
X_{1412}	30.1	X_{1412}	48.1	X_{1412}	
X_{1422}	85.9	X_{1422}	67.9	X_{1422}	116.0
X_{1523}	140.0	X_{1523}	140.0	X_{1523}	140.0
X_{1623}	57.0	X_{1623}	120.0	X_{1623}	120.0
X_{1633}	63.0	X_{1633}	-	X_{1633}	-
X_{1723}	14.0	X_{1723}	-	X_{1723}	60.7
X_{1733}	146.0	X_{1733}	160.0	X_{1733}	99.3
X_{1833}	11.0	X_{1833}	-	X_{1833}	-
X_{1843}	189.0	X_{1843}	200.0	X_{1843}	200.0
X_{1963}	100.0	X_{1963}	100.0	X_{1963}	100.0
X_{2043}	58.0	X_{2043}	90.3	X_{2043}	149.8
X_{2053}	92.0	X_{2053}	59.7	X_{2053}	0.2
X_{2123}	145.0	X_{2123}	145.0	X_{2123}	145.0
Total	2,191.0		2,191.0		2,191.0
$X_{ij} > 0$	35		27		27

X_{ijp} is the area of the management unit *i*, under the management prescription *j*, in the district *p*.

The forest regulation per district indicates different ways to manage the same units. For example, the management prescription X221 indicates the first harvest at the fourth year of the planning horizon. This represents harvesting trees at six years, when the new planting occurs. In the prescription X231, the harvest option would be, then, at seven years (maximum harvesting age), being, therefore, another option of conduction for such management unit. When carrying out the stratification per district (Scenario 1), the optimal solution for the forest regulation model indicated the harvest of 49 ha at the age of six years and 7 ha at the age of seven years. For the other two scenarios, the optimal solution indicated the harvest at the same point in the planning horizon, i.e. 56 ha to be harvested at the age of six years.

The volume produced each year of the planning horizon was similar in the three scenarios (Figure 1) and met the annual wood demand of 100.000 m3, allowing for the ± 20% variation. But, the annual yield, per district, was different for each scenario and the spatial constraint provided less variation in wood production (Table 6).

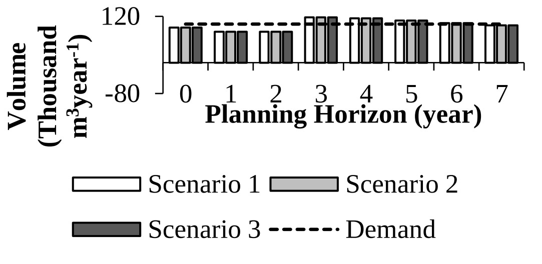

Figure 1 - Estimated volume of timber harvested annually from planted eucalypt stands in southeastern Brazil, considering the spatial stratification per district (Scenario 1), the annual volumetric production per district (Scenario 2) and the classic production regulation (Scenario 3)

Table 6 - Wood volume ($m^3 year^{-1}$) estimated to be harvested annually, in each district, in a case study of eucalypt stands in southeastern Brazil, considering the spatial stratification per district (scenario 1), the annual volumetric production per district (scenario 2) and the classic production regulation (scenario 3)

Planning horizon (years)	District 1	District 2	District 3	Total
Spatial stratification per district (Scenario 1)				
0	19,844	31,533	39,417	90,795
1	16,854	22,370	40,776	80,000
2	21,475	28,611	29,914	80,000
3	26,143	36,688	54,852	117,684
4	25,480	35,334	53,834	114,649
5	23,782	33,276	51,870	108,928
6	22,639	32,042	48,110	102,790
7	21,230	29,903	46,036	97,169
Annual volumetric production per district (Scenario 2)				
0	19,844	31,533	39,417	90,795
1	17,477	21,747	40,776	80,000
2	25,632	27,184	27,184	80,000
3	15,631	47,684	54,368	117,684
4	32,926	8,448	73,275	114,649
5	18,116	56,068	34,744	108,928
6	31,078	16,851	54,861	102,790
7	20,689	40,759	35,721	97,169
Classic production regulation (Scenario 3)				
0	19,844	31,533	39,417	90,795
1	16,854	22,370	40,776	80,000
2	26,314	26,502	27,184	80,000
3	15,631	32,621	69,431	117,684
4	32,926	24,948	56,775	114,649
5	28,171	46,013	34,744	108,928
6	6,180	29,312	67,298	102,790
7	35,977	40,234	20,957	97,169

Discussion

The equivalence of the optimal solution indicates that the spatial stratification per district, in the conditions of the present study, does not result in financial loss. However, it is not possible to assure that, for forest regulation problems with higher complexity (inclusion of other variables) and comprising a higher number of districts, there would be no reduction in the objective function value. Baskent (2001) highlights the sensitivity of the mathematic programming techniques regarding the number of decision variables. This author states that the incorporation of spatial relations promotes exponential increase in the processing (Baskent 2001).

The fragmentation of the management units is expected in forest planning models using linear programming (LP) (Silva et al. 2003). Although this is undesirable from the operational point of view, the LP was used for it is a fast and simple method for obtaining optimal solutions. Besides that, the purpose of the present study was to test the viability of the spatial stratification per district in forest production regulation models. The rounding of these solutions may be an alternative to solve this problem. However, this may cause impracticable solution (Silva et al. 2003, Goldbarg and Luna 2005). In this case, the use of integer programming or some heuristics is recommended to avoid the problem of the fragmentation of management units or stands (Rodrigues et al. 2003; Rodrigues et al. 2004a; Rodrigues et al. 2004b; Silva et al. 2009; Binoti et al. 2012).

The three scenarios generated the same global net of US$ 9.40 millions. This demonstrates that spatial stratification constraints do not penalize penalize the company profitability. However, the management options were differentiated. This indicates that each scenario represents different moments in which harvest and planting activities would be carried out in the management units. This implies different ways to manage the forest with the inclusion of spatial stratification per district.

The fluctuation of wood volume harvested annually, in each district, was lower when considering the spatial stratification constraint (Table 6); in this case, for the district 1, the wood variation ranged from 16,854 to 26,143 m3, while under the classic regulation; the variation ranged to 6,180 to 35,977 m3. For district 1, this variation in the annual volume produced was 55, 100 and 480%, for scenarios 1, 2 and 3, respectively. The spatial stratification constraint represents an enormous social contribution of this new scenario, because it guarantees annual harvest and smaller fluctuation in the volume harvested in all districts. In contrast, the classic regulation constraint, besides not guaranteeing annual harvests in each district, also promotes higher fluctuation of the wood volume harvested annually. For example, for district 1, the harvested volume varied from 6,000 to 40,000 m3, when considering the classic production regulation.

As demonstrated above, lower variation of the harvested wood volume implicates that the district income generated by tax collection over the forestry activities, will be uniformly distributed along the years. For the company, this reduced production fluctuation may indicate higher control over resources used in the production process, such as the use of equipment and labor and, therefore, it is possible to manage them sustainably and more efficiently. Therefore, the spatial stratification per district does not compromise the wood demand of the forest company.

A drawback that may appear from the use of this type of constraint refers to the supply of wood to the annual demand of the company once, in real conditions, there are districts with small areas of planted forest. Thus, aiming at guaranteeing that this demand is appropriately met, we recommend the grouping of the districts of small-planted area that are geographically close to each other.

Conclusions

The spatial stratification constraints per district at the regulation model results in the selection of a higher number of non-null decision variables, this fact guarantees annual harvest in each district, as well as smaller fluctuation in the volume harvested.

The spatial stratification per district, in the conditions of the present study, does not reduce the company's net income and does not influence meeting the company's wood demand.

The spatial stratification per district can result in lower wood volume fluctuation produced annually in each district and allows more efficient and sustainable management of the production process resources, such as the use of equipment and labor.

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