# A model to optimize the value of harvested species in a reduced impact logging concession system constrained by volume in the Brazilian Amazon

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## ABSTRACT

A new Brazilian law and regulation (# 11.284 dated March 02 2006; and # 6.063 dated March, 20 2007) created the Serviço Florestal Brasileiro (SFB) in March 2007. The SFB, or Brazilian Forest Service, manages zones designated for production within federal protected areas, including funding and technical assistance to develop a private concession system. An innovative bidding process, that weights the proposals on both technical quality (60%) and price (40%), guides the selection of future concessioners. The proposals are technically evaluated according to nine quantitative indicators grouped in four criteria: environmental impact; social benefits; efficiency; and locally added value. Concessioners explicitly declare estimates to the nine technical indicators, which are scored and weighted to compute a final single value used to qualify and classify the proposal. Among the nine indicators, there is one that specially deals with the diversity of species harvested to provide the 30 $m^3$ maximum volume allowed per hectare. The principle follows the hypothesis that, when constrained by volume, the harvesting of a large number of tree species maintains the residual forest diverse and rich, and promotes the introduction of potentially good new tree species in the timber market. Spatial considerations that affect costs and accessibility have also to be considered when choosing the set of trees that will approximately correspond to the desired amount of volume per species to be harvested. This paper describes a two phase solution technique to solve the problem: first, select the number of species and maximum volumes per species by means of a linear programming model; and secondly, locate the best trees in the field using a specially developed GIS routine. The solution technique was applied during feasibility tests implemented by SFB to evaluate the proposals presented to the first forest concession bidding process implemented in Brazil – the 2008 Jamari National Forest Concession Process.

Keywords: Linear programming, harvesting model, decision support system, forest management, concession.

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## Introduction

Up to the beginning of the 2000s, national forestry regulation and protection in Brazil were concentrated in the Instituto Brasileiro do Meio Ambiente e Recursos Naturais Renováveis (IBAMA), a broad environmental regulation agency headed by the Ministry of the Environment (Ministério do Meio Ambiente, MMA). Created in 1989 to protect and regulate the environmental, forestry, fisheries, and rubber sectors, IBAMA was also in charge of working with communities, specifically for the production of nontimber forest products in extractive reserves. Its mandate was to protect natural resources through "command and control" regulations. Over the years, experience accumulated until that date proved that approach proved not effective to manage the vast forests of the Amazon, given the relatively modest agency resources available.

In the 2000s, many interests convened processes that have changed substantially the Brazilian Forest Policy (Bauch et al., 2009). First, the National Forestry Program (Programa Nacional de Florestas) in the MMA proposed that the federal government shift its focus from only forest protection to forest development. The premise was that by creating opportunities to earn income from productive forests, they could be protected better than by command and control alone, partly by building alliances with interest groups who want to use and develop forest resources (e.g., Verissimo et al. 2002, 2004). Development would explicitly include timber harvest and concessions on public forest lands. For the first time in Brazilian history, forest concessions on public forests were supported by a comprehensive and detailed legal framework.

Specifically, the new Brazilian law and regulation (# 11.284 dated March 02 2006; and # 6.063 dated March, 20 2007) also paved the way for the creation of the Serviço Florestal Brasileiro (SFB) in March 2007. The SFB – or Brazilian Forest Service – became the manager of zones designated for production within federal protected areas, including funding and technical assistance to develop the private concession system. A complementary measure (law # 11.516/2007) entitled the creation of the new Instituto Chico Mendes de Conservação da Biodiversidade (with overall authority for all federal protected areas) based on a division of IBAMA. Basically, these laws maintained forestry responsibilities within the Ministério do Meio Ambiente, divided IBAMA's many authorities and responsibilities among three different branches of the agency, and provided the authority to decentralize many powers of IBAMA to states and municipalities.

Thus while the new laws provided opportunities for forest development, it also preserved the protection and regulatory components and structure of IBAMA. And simultaneously, with the creation of the Forest Service, a new space was created for new ideas about forest development within an existing strong institutional framework.

Among the new ideas, an innovative bidding process has been tested. Basically, the selection of future concessioners is based on a scoring system that weights the proposals on both technical quality (60%) and price (40%). The proposals are technically evaluated according to nine quantitative indicators grouped in four criteria: environmental impact; social benefits; efficiency; and locally added value. Concessioners explicitly declare estimates to the nine technical indicators, which are scored and weighted to compute a final single value used to qualify and classify the proposal.

Among the nine indicators, there is one that specially deals with the diversity of species harvested to provide the 30 $m^3$ maximum volume allowed per hectare. The principle follows the hypothesis that, when constrained by volume, the harvesting of a large number of tree species maintains the residual forest diverse and rich, and promotes the introduction of potentially good new tree species in the timber market. Spatial considerations that affect costs and accessibility have also to be considered when choosing the set of trees that will approximately correspond to the desired amount of volume per species to be harvested.

This paper describes a two phase solution technique to solve the problem: first, select the number of species and maximum volumes per species by means of a linear programming model; and secondly, locate the best trees in the field using a specially developed GIS routine.

**Materials and methods**

Harvest in the forest management concessional units follows the rational optimization economic principle of maximizing the timber value. Desirable outputs are related to tree species of commercial interest available in the forest. The chosen criterion to optimize desirable outputs is the maximization of revenues, either gross (price times volume) of net (gross revenue minus costs).

Mathematically, it is necessary to explicitly declare the constraints that limit the set of species chosen to maximize revenues when harvested. The set of constraints includes a few logical conditions like; (i) the maximum harvestable area; (ii) the maximum harvestable volume available of each species from trees with DBH above the minimum acceptable limit; and (iii) the maximum allowable volume to be extracted per hectare.

In the case of the concessions offered by the Brazilian Forest Service, two important sets of constraints also have to be considered. The first one imposes a minimum number of harvestable species per year, which was proposed by the concessioner during the bidding process. The second set considers the rule used to make the species eligible for the list of harvestable species.

In this work, the objective is to maximize total revenue subject to the following four simultaneous constraints:

i) The total annual harvested volume must generate an average less or equal to 30 m3/ha;
ii) The number of harvestable species must be equal to the value offered by the concessioner during the bidding process;
iii) The harvested volume of each species must be less or equal to the available volume estimated for all trees with acceptable DBHs (larger than 50 cm); and
iv) The total harvested volume of each species must be larger than a predefined admissible minimum (sufficient, for instance, to complete one truck load).

These conditions can be mathematically expressed as a linear programming problem. The mathematical model supporting the decision maker considers only two sets of variables: $X_i$ represents harvested volume of species $i$; and $Y_i$, a binary variable that tells whether the species $i$ was harvested (1) or not (0). Therefore, the problem becomes:

$$Max\ Z = \sum_{i=1}^{M} (p_i X_i)$$

subject to

$$(i)\quad \sum_{i=1}^{M} (X_i) \leq 30$$

$$(ii)\quad \sum_{i=1}^{M} (Y_i) = k$$

$$(iii)\quad X_i - v_i Y_i \leq 0 \quad \{i = 1,2,\dots,M\}$$

$$(iv)\quad wY_i - aX_i \leq 0 \quad \{i = 1,2,\dots,M\}$$

where: $p_i$ = value of a cubic meter of the $i^{th}$ species (R$/m$^3$)
k = number of harvested species in the forest management unit
$v_i$ = available volume of species $i$ in the forest management unit (m$^3$/ha)

| | |
|---|---|
| $w$ | = volume necessary to complete one truck load |
| $a$ | = area of the forest management unit (hectares) |
| $M$ | = total number of commercial species identified in the forest inventory |
| $i$ | $= 1, 2, ..., M$ |

**Results and discussion**

The Brazilian Saraca-Taquera National Forest was used to illustrate the analysis. The National Forest is located in the Brazilian Amazon in between Southern latitudes 1º20' and 1º55', and Western longitudes 56º00' and 57º15', on the side of the Trombetas River and occupying parts of the Faro, Oriximiná and Terra Santa municipalities.

Three forest management units in the Saraca-Taquera National Forest in Brazil, being offered by the Brazilian Forest Service in a bidding process, are used to illustrate the application of the suggested model. Basic information about these three forest management units is presented on Table 1.

Table 1: Estimated annual production area (APA) available in each forest management unit (FMU) in the Saraca-Taquera National Forest

| FMU | Total available area[1] | Area in the APA[2] |
|---|---|---|
| 1 | 90.000 | 3.000 |
| 2 | 30.000 | 1.000 |
| 3 | 18.600 | 620 |

[1] According to data published in the webpage of the Brazilian Forest Service, with area rounded to the closest hundred
[2] Considering a 30 year rotation

The total number of species identified in the Forest inventory assessment was slightly reduced to 97 (from the 104 originally identified) to maintain the problem size below the limit imposed by the solver found in the MS Excel spreadsheet used to develop the current application.

The objective function was set to maximize the total value of fees collected by the Brazilian Forest Service. Naturally, this was only used for the purpose of this exercise and does not reflect other situations where concessioners would be using real market values to guide their optimization analysis. Therefore, species were grouped in four categories according to four different fee values: R$ 120 for group 1; R$ 90 for group 2; R$ 50 for group 3 and R$ 25 for group 4. A total of 1.335 simulations were needed to cover all resulting scenarios that combine three sizes for the forest management unit, 89 different lists of harvested species (varying from 9 to 97 species) and five minimum volume rules for inclusion of the species in the list (truck loads of 20, 25, 30, 35 and 40 $m^3$).

Results obtained from each simulation are commented and presented in Figure 1, Figure 2 and Figure 3. Two optimal strategies for FMU 3, considering a minimum truck load of 30 $m^3$, are also presented to illustrate two scenarios: (i) one setting the harvestable number of species to 15, and a (ii) second scenario that sets this number to 40.

A strong effect on the results due to the emphasis of the optimization process on total gross revenue can be observed. The most valuable species are prioritized, seconded by the less valuable species which are indicated for harvesting only when absolutely needed.

Figure 1 considers the results observed for FMU 1 (3.000 ha) and shows the effect on the optimized value (total revenue) when the number of species assigned to harvest is varied from 9 to 97 species, and the minimum truck load rule varies according to values 20, 25, 30, 35 and 40 $m^3$. According to the results, it is possible to produce strategies with up to 37 harvested species and maintain the maximum optimized revenue unchanged at the level of R$ 3.391,26.

For lists with more than 37 harvested species, each increment of one species in the list results in a slight reduction in the optimal value. The reduction is due to the imposition of a maximum harvestable volume per hectare (30 $m^3$/ha), which makes the volume of a more valuable species be replaced by the volume of the less valuable species. In the exercise with FMU 1, when the list breaks the level of 37 harvested species in the list, new incoming less valuable species replaces more valuable species in the intermediate group (R$ 90,00 / $m^3$).

It is also important to notice that the rate of reduction is proportional to the minimum truck load used in each simulation. Larger truck loads are associated with larger rates of reduction. In the analysis involving FMU 1, for instance, the imposition of truck loads 20, 25, 30, 35 and 40 $m^3$, resulted in reduction rates of 0.27, 0.33, 0.40, 0.47 and 0.53 R$/ha, respectively. Another shift to a higher linear rate of reduction, observable in Figure 1, occurs when the list of species increases above 70 species. This is due to the fact that at this point the replaced species now belongs to the most valuable group (R$ 120,00 / $m^3$). At this level, the imposition of truck loads 20, 25, 30, 35 and 40 $m^3$ produces reduction rates of 0.43, 0.54, 0.65, 0.76 and 0.87 R$/ha, respectively.

The exercise with FMU 1 proved possible to generate strategies combining all 97 species and minimum truck loads. The "worst" scenario (97 species and a minimum truck load inclusion rule of 40 $m^3$) reduced the maximum gross revenue value in approximately 1,21%.

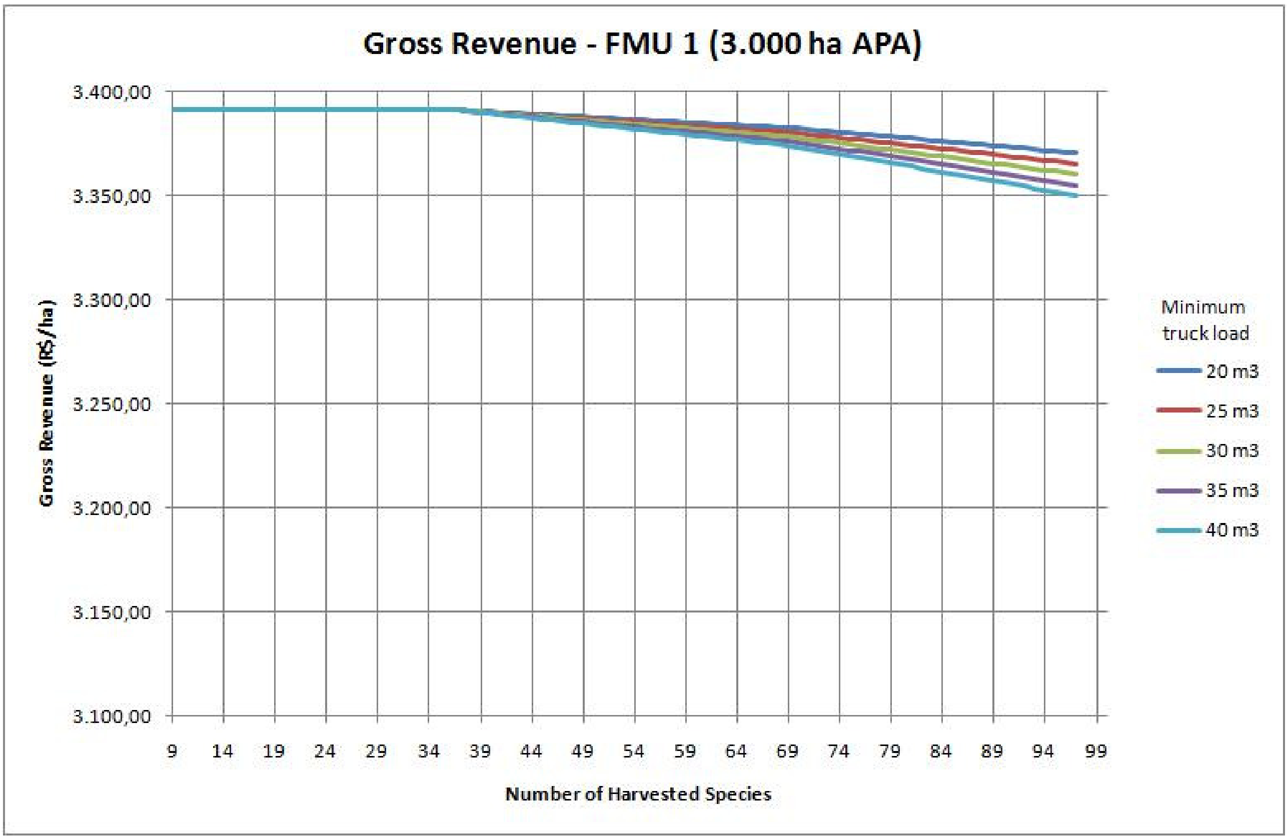


Figure 1: Effect on the maximum gross revenue per hectare of increasing the number of harvestable species subject to different minimum truck loads in FMU 1.

Figure 2 summarizes the results observed for FMU 2 (1.000 ha). According to the results, and similarly to FMU 1, it is possible to produce strategies with up to 37 harvested species, maintaining the maximum optimized revenue unchanged at the level of R$ 3.391,26.

For larger lists, each increment of one species in the list results in slightly larger reductions in the optimal value when compared to FMU 1. In the exercise with FMU 2, similarly to the exercise with FMU 1, when the harvestable list breaks the level of 37 species, new incoming less valuable species replaces more valuable species in the intermediate group (R$ 90,00 / $m^3$).

The imposition of larger minimum truck loads remain associated with larger rates of reduction. In the analysis involving FMU 2, the imposition of truck loads 20, 25, 30, 35 and 40 $m^3$, resulted in reduction rates of 0.80, 1.00, 1.20, 1.40 and 1.60 R$/ha, respectively. A shift to higher linear rate of reductions is also observable in Figure 2 and occurs when the list of species increases above 70 species. This is due to the fact that at this point the replaced species now belongs to the most valuable group (R$ 120,00 / $m^3$). At this level, the imposition of truck loads 20, 25, 30, 35 and 40 $m^3$ produces reduction rates of 1.30, 1.62, 1.95, 2.27 and 2.60 R$/ha, respectively.

The exercise with FMU 2 proved also possible to generate strategies combining all 97 species and minimum truck loads. The "worst" scenario (97 species and a minimum truck load inclusion rule of 40 $m^3$) reduced the maximum gross revenue per hectare in approximately 3,63%.

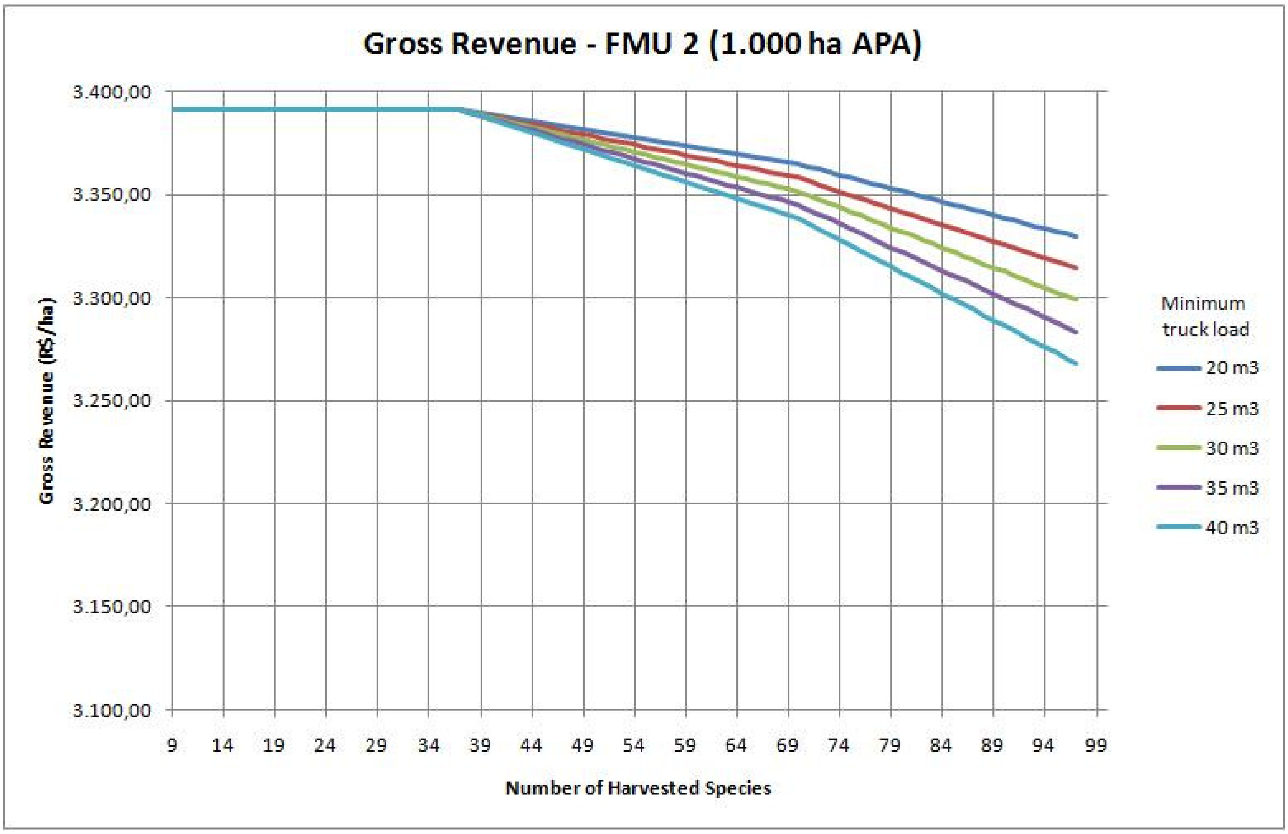


Figure 2: Effect on the maximum gross revenue per hectare of increasing the number of harvestable species subject to different minimum truck loads in FMU 2.

Figure 3 considers the results observed in a much smaller forest management unit. FMU 3 is a 620 hectares unit. According to the results, and differently from exercises with FMU 1 and FMU 2, the imposition of a minimum truck load of 35 and 40 $m^3$ has influence on the optimal strategy to harvest the forest unit. Strategies with up to 37 harvested species result in maximum revenue values of R$ 3.391,26 can be generated for minimum truck loads 20, 25 and 30 $m^3$. For a minimum truck load of 35 $m^3$ the same maximum revenue value is possible for lists with 36 or less species. For a minimum truck load of 40 $m^3$ it is possible to produce harvest plans with 34 or less species valued 3.389,36.

Above this levels, each increment of one species in the list also result in reductions in the optimal value as in exercises with FMU 1 and FMU 2. The exercise with FMU 3, similarly to the exercises with FMU 1 and FMU 3, also shows that the rate of reduction due to the fact that less valuable species replace more valuable species remains fixed over two intervals. In the first interval, when more valuable species in the R$ 90,00 / $m^3$ group are replaced, the reduction rates are 1.29, 1.61, 1.94, 2.26 and 2.58 R$/ha depending on the minimum truck load (R$ 90,00 / $m^3$). In the second interval, when species valued R$ 120,00 / $m^3$ are replaced, the rates of reduction become 2.10, 2.62, 3.15, 3.67 and 4.19 R$/ha, respectively, depending on the minimum truck load.

The exercise with FMU 3 also proved possible to generate strategies combining all 97 species, except for 35 $m^3$ and 40 $m^3$ minimum truck loads. Respectively, the largest list possible includes 96 species in the first case, and 94 species in the second case. The "worst" scenario (94 species and a minimum truck load inclusion rule of 40 $m^3$) reduced the maximum gross revenue per hectare in approximately 5,91%.

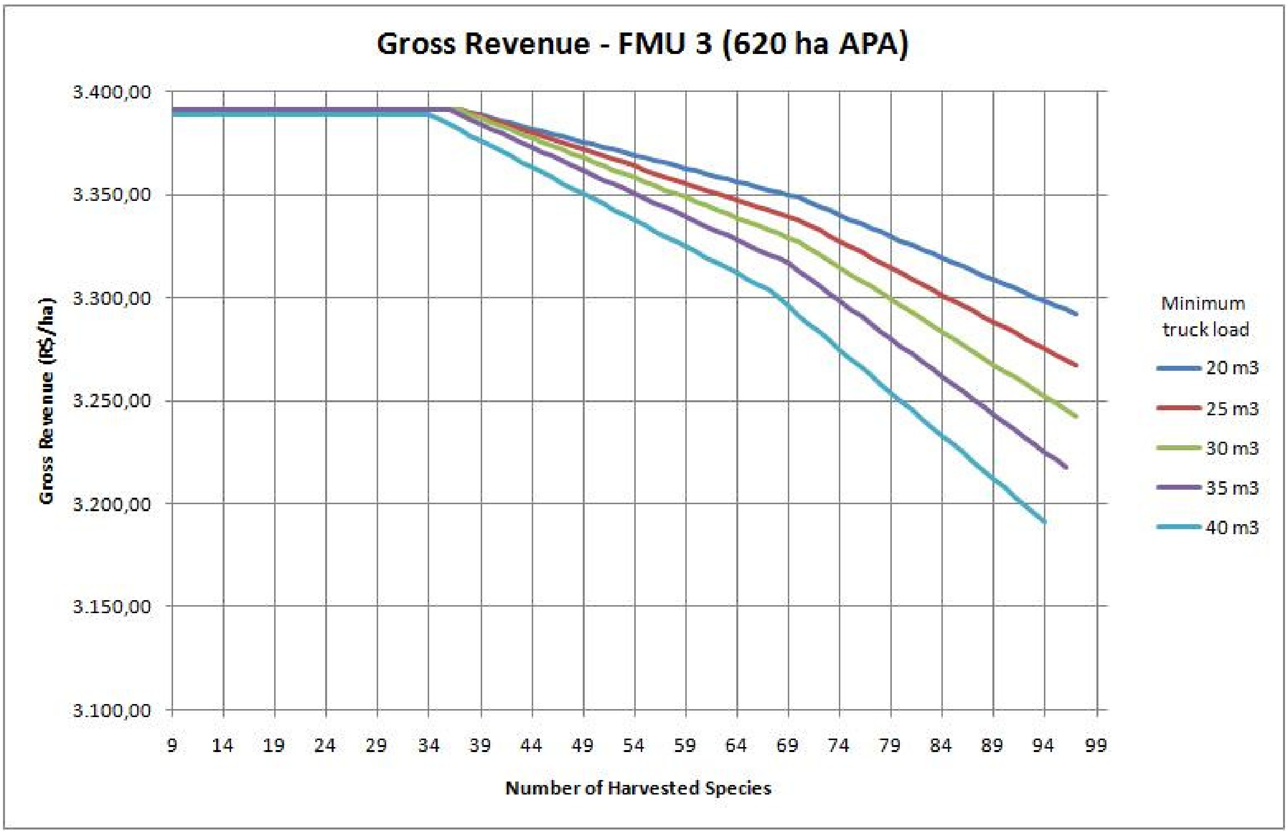


Figure 3: Effect on the maximum gross revenue per hectare of increasing the number of harvestable species subject to different minimum truck loads in FMU 3.

Table 2 and Table 3 summarize the results for FMU 3 according to two different simulations and allow a better understanding of the logical strategy provided by the mathematical model. One of the differences between the two strategies is the allowed size of the list of harvestable species. Table 2 lists the 15 species recommended by the linear programming model to be harvested. As expected, to complete the maximum mean harvestable volume per hectare (30 $m^3$), the solution provides a strategy where the total harvested volume comes mainly from trees belonging to the highest valued group of species. Therefore, Cumaru, Massaranduba, Maparajuba and Jatobá produce 70.7% of the total volume.

When the number of species is increased to 40 species, as in Table 3, the optimal solution maintains the same four species previously selected as the main source of volume producing exactly the same 70.7% of the total volumes. To complete the remaining volume, harvest is distributed among less valued species. More evidently, though, the new incoming less valuable species are included at its minimum amount necessary to just complete a truck load (average harvested volume per hectare x APA area = one truck load; that is 0.048387 $m^3$ x 620 ha = 30 $m^3$). This way, the average gross revenue per hectare is kept at its highest.

The second phase of the optimization process, which is the best selection possible of trees in the forest to provide the optimum volumes recommended by the model for each species, is now under development. A set of geographic information system tools is being tested to provide the location of these trees. Four layers including rivers spatial distribution, topography, trees location and road maps are combined with programming routines to facilitate the definition of the lowest harvest cost possible. Upcoming publications will disseminate the results of the analysis currently in progress related to the development of spatial analytical tools comprised in the second phase of the optimization process.

## Conclusions

A two phases planning method is suggested to adequately produce an optimized list of species to be harvested in tropical forests in the Amazon managed by concessioners. The method is applicable if the analyst has access to forest inventory data (including average commercial volume per species per hectare), the total area of the annual production unit and the average commercial value of a cubic meter for each species.

In the first phase, a mixed integer linear programming model is used to maximize gross revenue per hectare constrained by impositions such as maximum allowable harvest volume per hectare and limited by a fixed number of species to be harvested given each species produces a minimum total volume after the forest is cut. As expected in these cases, trees from the most valuable species contribute with most of the final total harvested volume. The model is efficient on evaluating the effect of increasing the number of harvested species. The mathematical approach produces an efficient replacement mechanism that optimally combines most valuable with less valuable species to produce a strategy that maximizes total revenues and respects the maximum allowable harvested volume per hectare.

A second phase must spatially apply the results of the first phase and produce a map with the exact location and wood transportation logistics that minimize costs and reduces environmental impacts. The work is currently developing this second phase.


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Table 2: Example of a simulation for FMU 3 involving 15 species in the harvestable list and a minimum truck load of $30m^3$

| | | | | |
|---|---|---|---|---|
| Max. harvestable volume ($m^3$/ha), V*: | 30,00 | APA area (ha): | | 620 |
| Harvestable number of species, S*: | 15 | Minimum truck load (m3): | | 30 |
| Total Average Revenue (R$/ha): | 3.391,26 | Average number of species and volume harvested per hectare: | 15 spp | 30 $m^3$ |

| ***Species*** | ***% harvested of available volume*** | ***% of total harvested volume*** | ***Volume ($m^3$/ha)*** | ***Value (R$/$m^3$)*** |
|---|---|---|---|---|
| Cumaru | 100,00% | 27,36% | 8,21 | 120 |
| Massaranduba | 100,00% | 25,96% | 7,79 | 120 |
| Maparajuba | 100,00% | 10,36% | 3,11 | 120 |
| Jatobá | 100,00% | 7,02% | 2,11 | 120 |
| Louro-preto | 71,84% | 5,07% | 1,52 | 90 |
| Pequiarana | 100,00% | 3,84% | 1,15 | 90 |
| Jutaí-pororoca | 100,00% | 3,63% | 1,09 | 90 |
| Sucupira-amarela | 100,00% | 3,51% | 1,05 | 90 |
| Muiracatiara | 100,00% | 3,09% | 0,93 | 120 |
| Tauari-vermelho | 100,00% | 3,07% | 0,92 | 90 |
| Angelim-Vermelho | 100,00% | 2,80% | 0,84 | 120 |
| Ripeiro | 100,00% | 2,73% | 0,82 | 90 |
| Louro-canela | 100,00% | 1,19% | 0,36 | 90 |
| Andiroba | 100,00% | 0,21% | 0,06 | 120 |
| Pequiá | 1,58% | 0,16% | 0,05 | 90 |

Table 3: Example of a simulation for FMU 3 involving 40 species in the harvestable list and a minimum truck load of $30m^3$

| | | | | |
|---|---|---|---|---|
| Max. harvestable volume (m3/ha), V*: | 30,00 | APA area (ha): | | 620 |
| Harvestable number of species, S*: | 40 | Minimum truck load (m3): | | 30 |
| Total Average Revenue (R$/ha): | 3.391,26 | Average number of species and volume harvested per hectare: | 40 spp | 30 $m^3$ |

| *Species* | *% harvested of available volume* | *% of total harvested volume* | *Volume ($m^3$/ha)* | *Value (R$/$m^3$)* |
|---|---|---|---|---|
| Cumaru | 100,00% | 27,36% | 8,21 | 120 |
| Massaranduba | 100,00% | 25,96% | 7,79 | 120 |
| Maparajuba | 100,00% | 10,36% | 3,11 | 120 |
| Jatobá | 100,00% | 7,02% | 2,11 | 120 |
| Pequiarana | 100,00% | 3,84% | 1,15 | 90 |
| Sucupira-amarela | 100,00% | 3,51% | 1,05 | 90 |
| Muiracatiara | 100,00% | 3,09% | 0,93 | 120 |
| Angelim-Vermelho | 100,00% | 2,80% | 0,84 | 120 |
| Ripeiro | 100,00% | 2,73% | 0,82 | 90 |
| Marupá | 100,00% | 2,50% | 0,75 | 90 |
| Itaúba | 11,87% | 2,41% | 0,72 | 90 |
| Louro-aritú | 100,00% | 2,25% | 0,68 | 90 |
| Cumarurana | 100,00% | 1,30% | 0,39 | 90 |
| Louro-amarelo | 100,00% | 0,64% | 0,19 | 90 |
| Andiroba | 100,00% | 0,21% | 0,06 | 120 |
| Sucupira-preta | 41,07% | 0,16% | 0,05 | 90 |
| Tauari-branco | 15,54% | 0,16% | 0,05 | 90 |
| Louro-canela | 13,56% | 0,16% | 0,05 | 90 |
| Louro | 57,53% | 0,16% | 0,05 | 90 |
| Preciosa | 30,81% | 0,16% | 0,05 | 90 |
| Quarubarana | 92,24% | 0,16% | 0,05 | 90 |
| Louro-gamela | 20,93% | 0,16% | 0,05 | 90 |
| Jutaí-pororoca | 4,44% | 0,16% | 0,05 | 90 |
| Louro-preto | 2,29% | 0,16% | 0,05 | 90 |
| Angelim-pedra | 1,10% | 0,16% | 0,05 | 90 |
| Louro-fofo | 53,69% | 0,16% | 0,05 | 90 |
| Tauari-vermelho | 5,25% | 0,16% | 0,05 | 90 |
| Ucuúba | 18,36% | 0,16% | 0,05 | 90 |
| Ucuúba-branca | 33,08% | 0,16% | 0,05 | 90 |
| Violeta | 53,69% | 0,16% | 0,05 | 90 |
| Virola | 38,21% | 0,16% | 0,05 | 90 |
| Cumaru-do-brejo | 16,49% | 0,16% | 0,05 | 90 |
| Louro-porco | 75,55% | 0,16% | 0,05 | 90 |
| Cupiúba | 0,91% | 0,16% | 0,05 | 90 |
| Angelim | 41,31% | 0,16% | 0,05 | 90 |
| Jutaí | 19,02% | 0,16% | 0,05 | 90 |
| Pequiá | 1,58% | 0,16% | 0,05 | 90 |
| Cubarana | 27,18% | 0,16% | 0,05 | 50 |
| Mata-mata-branco | 31,73% | 0,16% | 0,05 | 50 |
| Jarana | 21,65% | 0,16% | 0,05 | 50 |