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Using the Linear Programming in Mediterranean Forest Management : A Study Case from the North of Morocco

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Abstract— The multiple uses of Moroccan forest, the social context, and the limitation of traditional management methods makes it necessary to develop a new management method for forest management in Morocco. Therefore, the forest needs to be managed efficiently for multiple purposes.
The present study consists of developing a new management approach for Moroccan forests. This approach will be based on a linear programming model to provide an optimal solution to the current forest management problems. The relevance of the approach and its various components requires a prerequisite for the computerization of forest management in Morocco. This method will be applied to the pine forests in the Oued Laou watershed. The forest is located in the North of Morocco and contains three artificial plantations that are Aleppo pine, Maritime pine, and Monterey pine. They occupy 104 Hectares, 41 Hectares, and 349 Hectares, respectively.
To solve the linear programming model, 28 scenarios will be defined for all forests based on harvesting age, silviculture, and a planning horizon for the next 100 years, divided into 20 planning periods of 5 years.
The new model should satisfy a maximum of timber production while respecting various management constraints, including land availability, forest normality, sustainable timber volume, and the legal right of grazing. The optimal solution guarantees a volume of wood production equal to 105.753 m^3 while preserving the legal right of grazing. The irregular structure of forests will then be converted into a regular one.

Keywords— *management; forest; linear; programming; model; pine; maritime; Aleppo; Monterey; wood; constraints; solution.*

I. INTRODUCTION

Morocco has a privileged geographical location between the Mediterranean Sea in the North, the Atlantic Ocean in the West, and the Sahara desert in the South. It also has a variety of natural ecosystems with a great floristic and faunistic diversity (biodiversity). The forest part of it occupies a multipurpose area of approximately 9 million Hectares. However, Morocco's national forestation rate is limited at only 8% [1, 2].

Unfortunately, Morocco is currently producing only 20% of its timber needs [3, 4], making wood production and grazing the main policy of forest management in the country.

Even that 70% of Moroccan forests are managed; traditional management based on the manager's experience could not stop or anticipate the forest degradation in Morocco. Its limits are the subjectivity; it does not guarantee the united, equitable, sustainable, and conservative forest management. In addition, traditional management could not consider several objectives of forest uses.
Hence, the reflection on using a new forest management approach based on multi-objective tools.

Therefore, the limitation of the traditional management methods makes it necessary to develop a new management approach. Therefore, the forest needs to be managed efficiently for multiple uses [5, 6,7].

The study aims, through the integration of decision-support methods in forest management, to make a more objective forest management process and to improve forest planning in Morocco.

The linear programming method can be defined as a mathematical approach for solving management problems and, more particularly, those facing the manager [8, 9]. This method guarantees an optimal allocation of resources to achieve a specific objective, such as profit maximization or minimization of costs with several constraints [10, 11].

This method was first utilized around the sixties for the forest management and harvesting schedule by the United States of America and Canada [12, 13]. The models of linear programming will modernize the forest planning method and give managers rigorous and efficient planning tools, therefore improving the planning management process in the country [14, 15].

This study will provide a resolution to forest management challenges by utilizing linear programming tools that will promote multi-uses of Moroccan forest. Therefore, a linear management model will be developed for the pine forest located in the North of Morocco.

The forest contains three artificial plantations that are Aleppo pine, Maritime pine, and Monterey pine. They occupy 104 Hectares, 41 Hectares, and 349 Hectares, respectively. This model should satisfy a maximum of wood production while respecting various management constraints, including land availability, forest normality, sustainable timber volume, and the legal right of grazing.
The powerful simplex software of Lindo (Linear Interactive and Discrete Optimiser) will be used to solve the linear management model.

II. Related Work

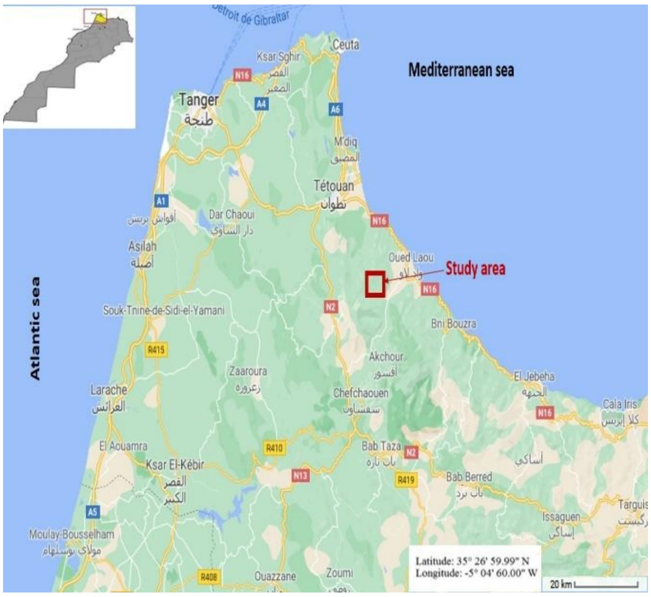
Related work in Mediterranean region is from Turkey, the title of the study is “Using Mixed Integer Goal Programming in Final Yield Harvest Planning: A Case Study from the Mediterranean Region of Turkey”.

Turkey has changed its classical forest management-planning model and implemented a functional ecosystem-based planning approach. Modern harvest planning is needed not only to ensure that a plan of action provided to foresters is efficient from an economic perspective, but also that it recognizes as many of the quantifiable management issues as possible to best represent a model of the management environment. Advances in operations research methods over the last four or five decades have informed the manner in which harvest planning is conducted in large forest management organizations.

The objective of the previous study is to develop and assess a mixed integer multi-objective model that addresses spatial forest planning problems involving time-space arrangements of regeneration sites [16].

III. Methodology

2.1. Study area.
The study area is located in the Oued Laou watershed in the Western Rif (North of Morocco), as shown in Figure 1. It is a part of the province of Tetouan, in the commons of Hamra, Beni Lait, and El Oued.



http://google.com/maps
***Figure 1.** Geographical site of the study area.*

The average annual rainfall in this area is between 604 mm and 1777 mm. The Temperature is relatively moderate and ranges monthly average from 12.7°C to 24.9°C. The climate is dry and of the Mediterranean type; the dry period lasts about 5 months. The seasons in the study area are Winter-spring-autumn-summer. The bioclimate is of sub-humid type; its temperature varies from hot to humid to moderate.

The survey samples of the Aleppo pine reforestation sites are found in all the exposed areas of moderately deep soils. The two types of substrates in the study area are sandy soil and loamy soil. Bioclimatic conditions are favorable. The floristic species are *Cistus monspeliensis* L., *Daphne gnidium* L., *Smilax aspera* L., *Nerium oleander L.*, *Arbutus unedo* L., *Phillyrea latifolia* L., *Myrtus communis* L., *Rubus ulmifolius* Schott.
The type of land uses in the study area are as follows: natural cork oak forest, artificial plantation based on Aleppo pine, maritime pine and Monterey pine, matorral, cereal-based agriculture, and arboriculture.

2.2. Methodology.
The methodology consist on formulation of objective functions and restrictions, then solving linear programs using “Lindo” software. The mathematical formulation of the model is as follows:

2.2.1. Linear programming model.
The linear programming model contains two parts: the first is the economic function representing the objective of the management, specifically the maximization of timber production. The second part addresses management requirements, namely the availability of lands, the sustainability of timber production, the forests normality, and the social constraint of grazing.

The economic function and constraints are written as linear mathematical equations according to the decision variables.

2.2.2. Developing objective function.
The study will focus on the artificial forests of Aleppo pine, Maritime pine, and Monterey pine. The objective is the maximization of wood produced by three forests:

$$MaximiserV = \sum_{i=1}^{n}\sum_{j=1}^{m}(Vij \times Xij) \quad \text{(Formula 1)}$$

i: management unit (i=1,n);
j: management alternative (j =1,m);
Xij: area of management unit (i) subject to the management alternative (j) in hectare;
Vij: wood volume harvested per hectare of the unit (i) subject to the management alternative (j) during the planning horizon in m3/ha;

2.2.3. Model restrictions (constraints).
-*Land or area constraint.*
This constraint is called the available resources constraint. It ensures that the variables of a given development unit are allocated on the area at least equal to its original area. The general formula for this constraint is as follows:

$$\sum_{i=1}^{n}\sum_{j=1}^{m} Xij = Si \quad \text{(Formula 2)}$$

i: management unit (i=1,n);
j: management alternative (j =1,m);
Si: total area occupied by the unit (i) in hectare;
Xij: management unit (i) subject to the management alternative (j) in hectare;

-*Constraint of wood production sustainability.*
From one planning period to another, the volume of wood produced should not fluctuate. This volume must be approximately the same for the regular forest. Thus, the wood industry will be working around the clock.
This constraint is written as follows:

$$Vk+1 \le Vk(1+\alpha) \quad \text{and}$$
$$Vk+1 \ge Vk(1-\beta) \quad \text{(Formula 3)}$$

Where:
α: positive fluctuations allowed (%) ;
β: negative fluctuations allowed (%);
Vk: wood volume harvested by different woodcuts during period k (m^3/ha);
Vijk: wood produced by the management unit (i) subject to management alternative (j) during period k (m^3/ha).
If fluctuations are not allowed, then we will have α = β = 0, the volume of wood produced during the period (k) is equal to that produced during the period (k + 1).

In this case, we will have:Vk= Vk+1

Were:

$$Vk+1 = \sum_{i=1}^{n}\sum_{j=1}^{m} Vij(k+1) \times Xij$$

and

$$Vk = \sum_{i=1}^{n}\sum_{j=1}^{m} Vijk \times Xij$$

i: management unit (i=1,n);
j: management alternative (j =1,m);
Xij: management unit area (i) assigned to the management alternative (j) in hectare;
-*Normal forest constraint.*
A normal structure of forests must be obtained at the end of the planning horizon.
The model requires a normal gradation of age classes for each forest plantation. We suppose that replanting is carried out automatically after harvesting action.
Therefore, the total area for each forest will be distributed equally among the age classes ranging from zero to revolution.
The general formula for this constraint is as follows:

$$\sum_{c=1}^{p} Xc = \frac{Xt}{P} \quad \text{(Formula 4)}$$

Xc: decision variable associated with planning alternatives that give the same age class at the end of the planning horizon.
Xt: total forest area (ha)
P: age classes number.
- *Grazing constraint.*
This constraint will guarantee the area's rate closed of grazing as recommended by Moroccan forest legislation. This rate is equal to 20 % of the total area. The duration of closing will depend on the age of defensibility of forests species. We consider that forest growth defenses will apply after planting. The time of its application will be 10 years for Maritime pine and Monterey pines, and 15 years for Aleppo pine. This constraint can be written as follows:

$$Xk \le \tfrac{1}{5} St \quad \text{(Formula 5)}$$

Where:
Xk: planting area during period k; (ha)
St: total area (ha).

IV. RESULTS AND DISCUSSION

3.1. Required information for model formulation.
3.1.1. Development units.
Each forest plantation will be considered as a management unit (Table.1)

Table 1. Management units identified in the plantations areas.

Forest plantation	management units (i)	Area (ha)	Current Stand Age (years)	Harvesting age (years)
Maritime Pine	1	41	36	40
Monterey Pine	2	349	35	35
Aleppo Pine	3	104	35	50

3.1.2. Horizon and planning period.

The planning horizon depends on forest harvesting age. It is generally equal to one and a half to two times this age [17]. Considering the three forests plantations, it was useful to retain two times Aleppo pine harvesting age, the oldest age. The planning horizon is 100 years. Considering the times between different silvicultural actions for the threes forests, the planning horizon is divided into five planning periods of 5 years.

3.1.3. Production parameters.

To estimate the wood production of forests plantations, we used volume rates. Tables 2, 3, and 4 show Silvicultural actions applied to Maritime pine, Monterey pine, and Allepo pine, respectively. The areas and growths parameters of forests are shown in table 5.

Table 2. Silvicultural actions applied to Maritime pine [18,19].

Age	Silvicultural Actions	Products	Number of cut trees /ha	Volume (m^3/ha)
0	Planting	***	***	***
3	Pruning 1	***	***	***
9	Pruning 2	***	***	***
15	Thinning 1	Fuelwood	550	57,5
16	Pruning 3	***	***	***
20	Thinning 2	Service wood	180	22,2
25	Thinning 3	Service wood	120	11,4
40	Clear cutting	Service wood	250	148,5

Table 3. Silvicultural actions applied to Monterey pine [19,20].

Age	Silvicultural Actions	Products	Number of cut trees /ha	Volume (m^3/ha)
0	Plantation	***	***	***
6	Pruning 1	***	***	***
12	Pruning 2	***	***	***
15	Thinning 1+	Fuelwood	550	37,8
20	Thinning 2+	Service	180	46,4
25	Thinning 3+	Service	220	59,3
35	Clear cutting	Service	150	64,5
Total	***	***	1100	208

Table 4. Silvicultural actions applied to Aleppo pine [20,21].

Age	Silvicultural Actions	Products	Number of cut trees/ha	Volume (m^3/ha)
0	Plantation	***	***	***
3 à 6	Pruning 1	***	***	***
13	Pruning 2	***	***	***
16	Pruning 3	***	***	***
20	Thinning 1	Fuelwood	400	44,2
24	Thinning 2	Service wood	130	21,5
30	Thinning 3	Service wood	90	14,8
50	Clear cutting	Service wood	180	44,4
Total	***	***	800	124,9

Table 5. Areas and dendrometric characteristics.

Species	Mean age (years)	Area (ha)	Volume of trees(m^3/ha)	Mean annual Increase (m^3/ha/an)
Maritime pine :		41		
-Site A :	36	21,6	296,1	6,2
-Site B :	36	19,4	174,9	4,4
Monterey pine :		349		
- Site A:	35	183,7	219,6	8,2
- Site B :	35	165,3	154,8	4,7
Aleppo pine :	35	104	145,2	3,8

3.1.4. Stand volume tariffs.

This tariff quickly gives the volume of forest stands by taking measurements of stand characteristics. The tables 6 shows stand volume tariffs.

Table 6. Stand volume tariffs.

Forest speceis	Stand volume tariffs
Maritime pine	$V = -38,39 + 1,93\ Hg + 6,53\ G$
Monetery pine	$V = -40,59 + 6,17\ G + 0,252\ Hg$
Aleppo pine	$V = -31,46 + 1,81\ Hg + 3,94\ G$

Note: *V* is volume, m^3/ha; *G* basal surface, m^2/ha; *H*g is the average arithmetic height of stands, m;

3.2. Model solution.

There are several software for solving linear programs, but the most popular one is “Lindo” which uses the powerful algorithm of the simplex. It is software used to solve linear integer and quadratic optimization models and offers tools to help analyze solutions. Version 6.0 is used to solve maximum dimension problems of 200 variables and 100 constraints.

To examine the effects of each constraint on management objectives, the linear programming model related to the maximization of wood production was firstly solved with a single constraint at a time and then by combining all the constraints of management.

The complete results of the management models are shown in Table 7:

Table 7. Model solution with constraints effect analysis.

Models	**Fluctuation of wood production (%)**	**Total wood Production (m^3)**	**Reduction from model without constraint (%)**
Land constraint (model without constraint)	- - -	206.027	0
Grazing		141.108	31,51
Normality		190.575	7,5
Sustainability of	0	Infeasible solution	

Wood production	5	Infeasible solution	
	10	Infeasible solution	
	15	180.232	12,52
All the constraints of the management	15	no solution	
	20	no solution	
	30	no solution	
	40	no solution	
	45	105.753	48,67

3.3. Discussion:
Solving the model with only a land constraint gives timber production of 206.027 m^3 over the planning horizon. It produces an annual volume of $4,2m^3$/ha, which is above the average obtained for pines forests managed by traditional methods (knowing that 75% of pines forest in North Morocco has an annual production lower than 1 m^3/ ha and the rest between 1 and 2 m^3/ha /year).

When grazing constraint is applied to the model, the volume harvested is 141.108 m^3 over the planning horizon, representing 31,51% less than the volume of the model without constraint.
The model with a forest Normality constraint offers a total wood volume of 190.575 m^3, which represents 7.5% less than the volume of model without constraint.
The model with a sustainability constraint does not offer a solution for 0, 5 and 10 % of volume fluctuation from one period to another. The solution becomes feasible for 15% of volume fluctuation from one period to another and gives a total wood volume of 180.232 m^3, representing 12,52 % less if no constraint is applied. This shows the importance of the volume of wood that is lost to ensure harvest wood sustainability, which is a fundamental principle of forest management that is needed to be satisfied.

By applying all the constraints of management models, even with 15% fluctuations, the solution is not feasible. It is only feasible by tolerating the fluctuations of 45% in periodic timber production due to the possible cause of irregularity of forests in the beginning. In this case, the optimal solution of the management model related to the objective of maximizing wood production with all the constraints gives a total volume of 105.753 m^3 of timber. That makes an annual wood production of $2,13m^3$/ha, which is above the average obtained for pine forests plantations managed traditionally in the same area.
There is a reduction in wood production of 48,7 % compared to the value of the same model without constraint.
Therefore, the wood volume production loosed in this case is 100.273 m^3 over the planning horizon. To ensure a sustained yield, forest normality and grazing rate should not exceed 20% of each forest plantation.

3.3.1. Forest normality.
The optimal solution of the management model related to the objective of maximizing wood production with all the constraints gives a total volume of 105.753 m^3 of timber. That makes an annual wood production of 2,13 m^3/ha, which is above the average obtained for pine forests plantations managed traditionally in the same area.
When all management constraints are applied simultaneously to the model, all age classes are represented with the same areas. Therefore, we obtain normal forests at the end of the planning horizon.

3.3.2. Wood production sustainability.
The analysis of this optimal solution in figure 2 shows that the periodic volumes vary from 3489.8 m^3 in the 3rd period to 7402 m^3 in the 1st period. The average periodic volume is $5287m^3$, 10 periods out of 20 have reached this average, but fluctuations still exist around 45%.

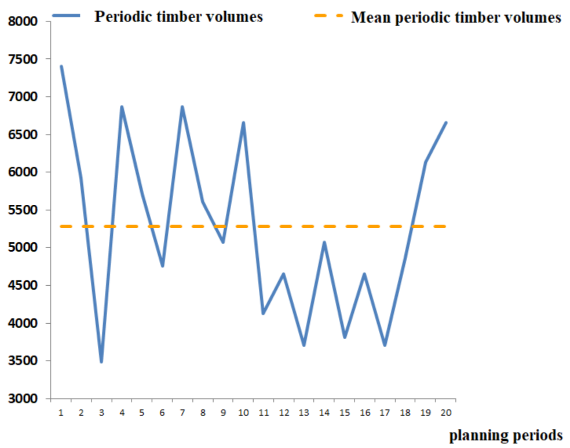


Figure 2. Fluctuations in periodic timber volumes - effect of all constraints.

3.3.3. Defending area from grazing.
The duration of closing will be 10 years for Maritime pine and Monterey pines, and 15 years for Aleppo pine. The defending rate required by Moroccan law is:
- 8,2 ha for maritime pine,
- 69,8 ha for Monterey pine,
- 20,8 ha for Alep pine.

The solution given by the model shows that the grazing rate recommended by the forest legislation is respected overall planning horizons, as indicated in table 8.

Table 8. Distribution of defended areas from grazing.

Planning Periods	**Area defended area from grazing(ha)**		
	Maritime Pine	Monterey pine	Aleppo Pine
1	0	0	0
2	0	0	0
3	0	0	0
4	15,5	72,8	30,3
5	11,4	89,4	23,3
6	9,2	76,6	21,7
7	8,8	86,8	20,8
8	8,2	88,5	20,8
9	8,2	73,7	20,8
10	8,2	69,8	20,8

11	8,2	69,8	20,8
12	8,2	69,8	20,8
13	8,2	69,8	20,8
14	8,2	69,8	20,8
15	8,2	69,8	20,8
16	8,2	69,8	20,8
17	8,2	69,8	20,8
18	8,2	69,8	20,8
19	8,2	69,8	20,8
20	8,2	69,8	20,8

3.3.4. Silvicultural actions.

The solution of the management model allows defining of the most appropriate silvicultural actions to be applied to the forest plantations. It is given by analyzing the best management scenario for each forest given by the model. Silvicultural actions were applied to maritime pine, Aleppo pine, and Monterey pine, are shown in the following tables 9, 10 and 11:

Table 9. Silvicultural actions to be applied to maritime pine given by linear model.

Planning periods	Age (years)	Silvicultural actions
2	40	Clear cutting and plantation
	3-6	1st thinning
	9	2nd thinning
	15	1st pruning
	16	3rd thinning
	20	2nd pruning
	25	3rd pruning
11	40	Clear cutting and plantation
	3-6	1st thinning
	9	2nd thinning
	15	1st pruning
	16	3rd thinning
	20	2nd pruning
	25	3rd pruning
20	40	Clear cutting and plantation

Table 10. Silvicultural actions to be applied to Aleppo pine given by linear model.

Planning Periods	Age (years)	Silvicultural actions
4	50	Clear cutting and plantation
	3-6	1st thinning
	13	2nd thinning
	20	1st pruning
	24	2nd pruning
	30	3rd pruning
14	50	Clear cutting and plantation
	3-6	1st thinning
	13	2nd thinning
	20	1st pruning
	24	2nd pruning
20	30	3rd pruning

Table 11. Silvicultural actions to be applied to Monterey pine given by linear model.

Planning Periods	Age (years)	Silvicultural actions
1	35	Clear cutting and plantation
	6	1st thinning
	12	2nd thinning
	15	Thinning 1+ Pruning 3
	20	Thinning 2+ pruning 4
	25	Thinning 3+ pruning 5
8	35	Clear cutting and plantation
	6	1st thinning
	12	2nd thinning
	15	Thinning 1+ Pruning 3
	20	Thinning 2+ pruning 4
	25	Thinning 3+ pruning 5
15	40	Clear cutting and plantation
	6	1st thinning
	12	2nd thinning
	15	Thinning 1+ Pruning 3

V. CONCLUSION AND FUTURE SCOPE

The objective of this study was to design a new management method for the Moroccan forest. The approach consisted of developing and solving management models using linear programming, which was applied to pines forests located in the Oued Laou watershed. The forest is located in the North of Morocco and contains three artificial plantations that are Aleppo pine, Maritime pine, and Monterey pine. They occupy 104 Hectares, 41 Hectares, and 349 Hectares, respectively.

The model should satisfy a maximum of wood production while respecting various management constraints, including land availability, forest normality, sustainable timber volume, and the legal right of grazing.
To solve the forest management model by using linear programming, a total of 28 scenarios have been defined for all forests based on harvesting age, silviculture, and a planning horizon for the next 100 years, divided into 20 planning periods of 5 years. The optimal solution of the model became feasible by accepting 45% periodic volume fluctuations from one period to another. That represent 12,52 % less of wood volume if no constraint is applied. This shows the volume of wood that is lost to ensure harvest wood sustainability, which is a fundamental principle of forest management that is needed to be satisfied.

The model guaranteed a volume of wood production equal to 105.753m^3 while preserving the legal right of grazing. It produces an annual volume of 2,14 m3/ha, which is above the average obtained for pines forests managed by traditional methods (knowing that 75% of pines forest in North Morocco has an annual production lower than 1 m3/ ha and the rest between 1 and 2 m3/ha /year).

The irregular structure of forests was then converted into a regular one. The model with a forest Normality constraint offers a total wood volume of 190.575m3, which represents 7.5% less than the volume of model without constraint.

The solution of the management model allows defining of the most appropriate silvicultural actions to be applied to the forest plantations. It is given by analyzing the best management scenario for each pine forest.

According to the context of the application of the proposed method, we can conclude that the linear programming model is a powerful tool for forest management in Morocco. It allows a massive amount of data to be to analyzed. This approach will reduce the overall forest management costs. The prospect of its adoption by the Department of Water and Forest requires integrating its components in a computerized database. Also, it is important to establish production tables for the natural and artificial forest species in Morocco.

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