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Forest production management and harvesting scheduling using dynamic Linear Programming (LP) models

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Abstract

Fuelwood is one of the most widely used natural resources. Its major uses include household heating and energy production (heat energy plants). Its production is expected to increase in order to cover the increased demand, therefore management of fuelwood productive forests should be done in a sustainable way. Two linear programming (LP) models are presented in this work, for the optimal design of production and harvesting scheduling of fuelwood, produced from even-aged (coppice) Oak forests. Respectively, two alternative sustainable management strategies are examined. The first strategy aims at sustainable fuelwood production in the context of area control. The second one achieves maximization of the volume per unit of time and leads to a steady state forest. Actual data from the forest management plan of Achladochori-Aggistro-Sidirokastro forest are used to demonstrate models application. Both models can serve as a “rule of thumb” in the forest management practice.

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Keywords: Fuelwood production; Coppice forest; Sustainable forest management; management alternatives; linear programming (LP)

1. Introduction

Forests produce a great variety of timber and non–timber products and services [1, 17, 18]. Although the importance of non-timber forest services has increased in the last decades, the high oil prices and the current

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economic crisis have turned focus on fuelwood as heating source as well. The increased household consumption of fuelwood in the recent years has developed a fast growing market in Greece [2, 3], with great price fluctuations over time [4, 5]. Moreover, the use of biomass as raw material for energy production in the frame of the European policy objectives 20-20-20 (reducing greenhouse gas emissions by 20%, increasing the share of renewables in energy consumption to 20% and improving energy efficiency by 20%, all by 2020) would demand higher quantities of fuelwood used for this purpose. Consequently, forest management decisions concerning fuelwood production planning is crucial for the sustainable development of the respective fuelwood market.

In the relevant literature, forest production planning is best described by the use of mathematical programming [6]. The aim of such forest production models is to maximize the volume that would be eventually harvested. Furthermore, maximization of harvest volumes may lead to larger marginal profits if it is accompanied by restrictions on harvested quantities in order to increase the total area that would be regenerated at the end of each planning season [7]. In addition to volume control, area control and non-declining even flow of timber are common criteria used in forest management modelling [8]. Besides maximization of harvested quantities, constraints related to ecological or aesthetic reasons [8], as well as to conservation of biodiversity are also examined [9]. Post production problems are usually connected with the distribution of the products to different nodes of a supply chain network (Agriculture Forest Cooperatives, fuelwood merchants, customers) [10]. Extensions of supply chains under stochastic (normally distributed) demand have been also proposed [11]. Due to the multidimensionality of the problems, it is common that single objective function models do not provide adequate description of natural resource problems. When more than one objective is required multi-objective optimization models are used [12].

In this work, a dynamic, linear programming (LP) model is presented, for the optimal design of production and harvesting scheduling of fuelwood, produced from even-aged (coppice) Oak forests, under two alternative sustainable management strategies. Actual data from the forest management plan of Achladochori-Aggistro-Sidirokastro forest [19] are used to demonstrate model's application.

Nomenclature

c	Age class
t	Time period
K	Logged volume of fuelwood (m^3)
V_c	Volume of age class c (m^3)
$F_{c,t}$	Initial area of age class c, year t (ha)
$f_{c,t}$	Logged area of age class c, year t (ha)

2. Fuelwood production and Mathematical mode

The major fuelwood production in Greece comes from Oak coppice forests [13] through clear cutting in relatively small areas, which results in the creation of even-aged stands. The rotation age is 20-25 years, defined as the stand age that maximizes the volume produced per unit of time. To facilitate management planning, clear cut areas are classified into 5-year age classes and treated together as stands with similar characteristics. Assuming a rotation age of 20 years and similar growing capacity (site quality) of the stands, each age class must hold an area equal to ¼ (the so called "normal" area) of the total forest area in order to guarantee sustainable production [14, 15]. That is, the equality of area available for clear-cutting every 5-year periods produces the same fuelwood quantity ad infinitum. Therefore, the first objective of sustainable forest management in this case is the achievement of the area equality between age classes, while maximizing the wood production from the entire forest.

Depending on the initial conditions of a forest, i.e. the distribution of the various stands in age classes, it is possible that the sustainable conditions (equal area among classes) cannot be achieved during a rotation period. Cutting of young immature stands or stands beyond the rotation age are common reasons for such conditions that do not permit application of the above sustainability scheme. In such a case, an alternative sustainable management scheme is to aim at the creation of a steady state in the forest, that is, a state where the initial area in each age class is the same in two successive rotations [8].

Objective of the proposed models is the maximization of the logged volume of fuelwood (K). The total logged fuelwood quantities are calculated as the sum of products of growing stock (volume) of all age classes c (V_c) and the logging area of the respective classes c in time horizon t ($f_{c,t}$). The objective function is described by the following mathematical notation:

$$\max \ K = \sum_c \left(V_c \cdot \sum_t f_{c,t} \right) \tag{1}$$

Harvested fuelwood quantities are subject to specific constraints posed by the management alternative. The models for both management alternatives presented above are described in the following chapters. The actual data of the example forest are used in an illustrative case. The growing stock of each stand is calculated by the use of the relevant Yield Tables [16].

2.1. First model – fuelwood production sustainability

In order to guarantee the fuelwood production sustainability several constraints should be introduced regarding the balance of the logged area. The planning horizon is set to 20 years, coinciding with the rotation time and forest stands (clear-cut areas) are classified into 5-year age classes (c). Thus, the age class distribution of the forest can be structured every 5-year time periods (t). A general constraint regarding the logged area is that it cannot exceed the initial area of each class c in time t (F_{ct}). This can be modeled with the following inequality:

$$F_{c,t} \geq f_{c,t}, \ \forall c,t \tag{2}$$

For every time period, the area of the first age class must be equal to the area that was logged in the previous period. This leads to the following constraint regarding the transfer of the logged area to the first age class:

$$F_{c=1,t} = \sum_c f_{c,t}, \ \forall t > 2 \tag{3}$$

The area of every next age class of the rotation (2nd – 4th), for each time period, is calculated by the subtraction of the logged area of the previous age class from the total area of the same age class in the preceding time period. The respective constraint is:

$$F_{c,t} = F_{c-1,t-1} - f_{c-1,t-1}, \ \forall c > 2, t > 2 \tag{4}$$

In case of existence of over-mature stands (ages greater than the rotation time) a fifth age class should be considered. The area of this age class for each time period is calculated by subtracting the logged area of the 4th and 5th age classes from the initial area of the same age classes in the preceding time period. The respective constraint is:

$$F_{5,t} \ = \ F_{5,t-1} - f_{5,t-1} + F_{4,t-1} + f_{4,t-1}, \forall t > 1 \tag{5}$$

Finally, the fuelwood production sustainability calls for equal areas among age classes at the end of the planning horizon, i.e. at time t_5, introducing the following constraint:

$$F_{c,t=5} = F_{c+1,t=5}, \ \forall c \tag{6}$$

The first model consists of the objective function (1) and the production/scheduling constraints (2) – (6). The data of the example forest are presented in Table 1. The results of model application are summarized in Figure 1.

Logged areas from the late age classes are transferred after clear-cut into the first class and areas of intermediate age classes are passing to the next age class every 5-years period. The surplus of area in the older ages allows heavy logging in the first period, while in the following periods the “normal” area is harvested. The initially irregular area distribution among age classes (t_1) is transformed at the end of the planning horizon (t_5) into an even distribution that guarantees sustainable fuelwood production from the forest.

Table 1. Data of the example forest: initial area and mean fuelwood production per hectare for every age class

Age class (*c*)	Initial Area $F_{c,t=1}$ (*ha*)	Fuelwood volume, V_c (m^3/ha)
1 (1-5 yrs)	0	0
2 (6-10 yrs)	90	0
3 (11-15 yrs)	780	60
4 (16-20 yrs)	959	89
5 (21-25 yrs)	886	117

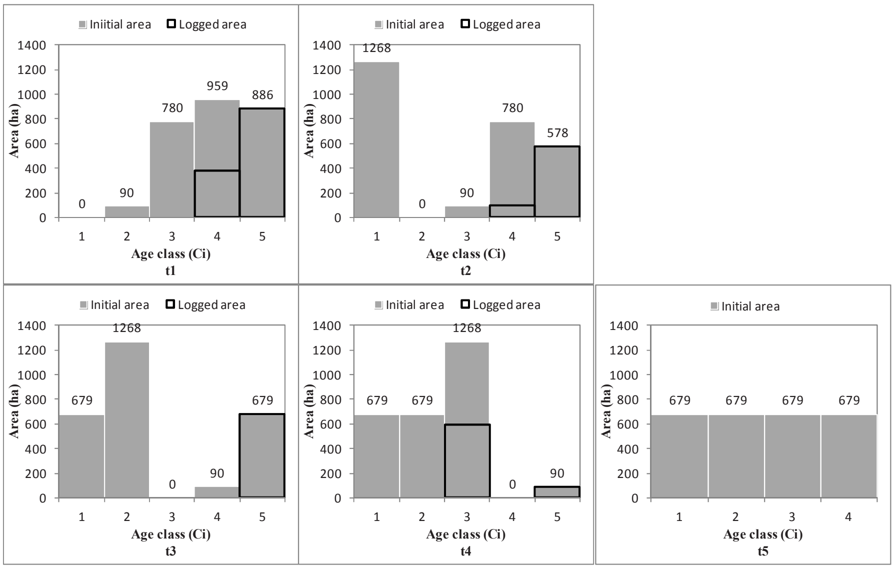

Fig. 1. Initial and logged area distribution (ha) in age class *c* at time *t*, for the entire planning horizon under the first management alternative.

2.2. Second model – steady state forest

In this model the sustainability of fuelwood production is relaxed to a steady state forest. Forest stands are logged as they reach the rotation age, providing for maximum production per unit of time and creating – by the end of the planning horizon – a situation that can be continuously repeated in the future. In this steady state situation the area in each age class is the same in two successive rotations.

Logging at rotation age implies that the entire area of the 4th and older age classes should be logged and poses the next constraint:

$$F_{c,t} = f_{c,t},\ c \geq 4, \forall t \tag{7}$$

The constraints (2) to (5) developed for first model define the structure of the area distribution in the intermediate age classes and are valid in the second model as well.

The LP model that describes the steady state production scheme is formed with objective function (1) subject to constraints (2) – (5), (7). The results of model application to the example coppice forest are presented in Figure 2.

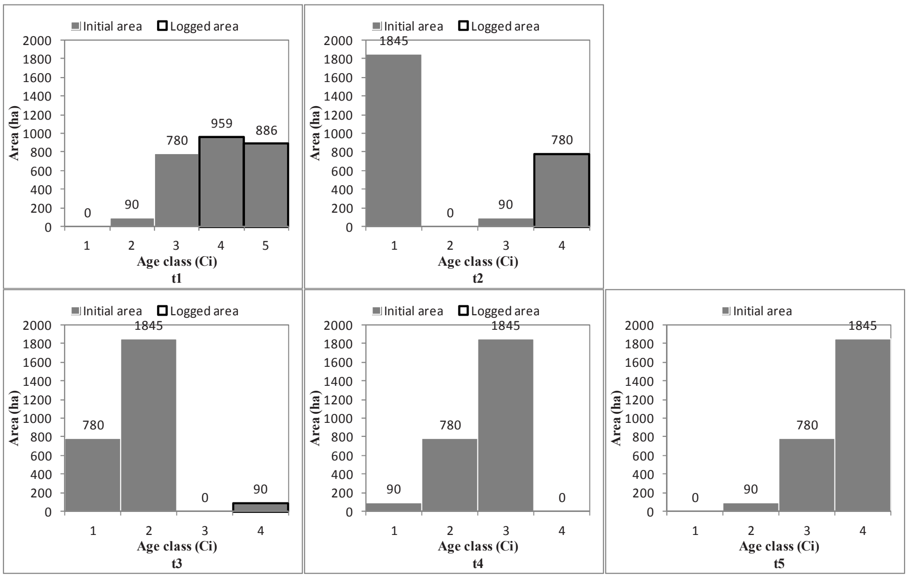

Fig. 2. Initial and logged area distribution (ha) in age class *c* at time *t*, for the entire planning horizon under the second management alternative.

As forest stands are logged at the rotation time, stands in the 4th and 5th age classes are harvested in the first time period. The existence of over-mature stands alters the initial structure by almost doubling the area of the 1st class at t2. After this change areas are passing to the next age classes as time passes. In the next time periods only stands of the 4th age class is permitted to be logged. Consequently, the so formed area distribution is perpetuated. Great differences in the area among age classes imply also great differences in fuelwood production. The final steady state comprises one 5-years period with very high production followed by a period with medium production, a period with very small and a last period with null production.

3. Conclusions

Two alternative forest management strategies applied in the management planning of coppice forest for fuelwood production have been modeled using LP in this paper. Both models aim at maximization of the quantity of fuelwood produced under constraints posed by the alternative strategies.

In the first LP model, where fuelwood production sustainability is guaranteed, an initially irregular distribution of area into age classes is being gradually transformed into a uniform distribution. This ensures a steady supply of fuelwood to the market by the end of the planning horizon (rotation time). Differences in the production among 5-year periods could occur due to differences in the production potential of stands in the same age class. Therefore, before applying the model an adjustment of the areas according to the site quality of the stands (production potential) should be made.

On the contrary using the second LP model, the initial irregularities in the area distribution into age classes are kept in perpetuity. The only possible change in the distribution can arise from existence of over-mature stands, but the final distribution will continue to be uneven. Consequently the market supply would present great fluctuations, depending on the differences in area among successive age classes.

Both models can be useful to the forest management practice. The calculation of the maximum production level, which is expected under the alternative chosen to be applied, is simple and easy. The comparison of the final age class distributions of the two alternatives can lead also to useful conclusions cornering the future development of the forest.

The first alternative, which incorporates the concept of “normal forest” and is attractive to foresters, can be assessed in terms of cost (economical but also ecological) paid to achieve the normal conditions. The ecological drawback of young, immature stands logged to accomplish the equality of areas should be compensated by the economic benefit of securing steady fuelwood supply.

The second alternative achieves maximum production per unit of time and is ecologically preferable since the stands are logged at their maturity. But it could be economically unfavorable in cases of a well developed fuelwood market which demands constantly high quantities of raw material.

Both presented models have advantages and disadvantages, which should be assessed with respect to the situation created by their application to the forest. They model the two most common alternatives faced by the forest managers and could be useful as a rule of thumb in making rational decisions.

A third alternative usually followed in the forest management practice is an intermediate route, which smoothes the differences in the area distribution among age classes without leading to a uniform situation. Modeling this alternative requires more sophisticated models, which apart from the age class and the production potential they incorporate the spatial position and the silvicultural treatments of the stands.

Fuelwood production defined as logged volume was the objective function in both models. Other economic criteria, such as the market value or the profit of the produced fuelwood, could have also been used. Logged volume was preferred, since we are dealing with a single product and its volume is directly proportional to its value. Moreover, economic criteria demand additional data related to yearly fuelwood prices and harvesting costs. Such data are currently collected and respective models will be elaborated in the near future.

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