Jul 1st, 12:00 AM

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iEMSs 2008: International Congress on Environmental Modelling and Software
Integrating Sciences and Information Technology for Environmental Assessment and Decision Making
4th Biennial Meeting of iEMSs, http://www.iemss.org/iemss2008/index.php?n=Main.Proceedings
M. Sànchez-Marrè, J. Béjar, J. Comas, A. Rizzoli and G. Guariso (Eds.)
International Environmental Modelling and Software Society (iEMSs), 2008

Forest Biomass Sustainable Use for Energy Production: a dynamic optimization problem

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Abstract: The use of forest biomass for energy production requires a careful attention to the sustainable silvicultural practices that can guarantee the satisfaction of the environmental constraints, the control of the forest growth, the carbon stock, and the CO_2 emissions. This is a complex task because of the different environmental and economic issues (related to the characteristics of the territory, the energy demand, the forest biomass potential production, and the techniques for forest utilization) to be taken into account. Environmental Decision Support Systems (EDSS) are considered as valuable tools for the planning and management of renewable resources use for energy production. In this paper, an EDSS for the tactical planning of forest biomass use (i.e., for the planning over a medium-short term horizon, within a discrete-time setting and the assumption that the plant capacity and the sizing of all facilities are known) is proposed. In particular, attention is focused on a dynamic decision model. An optimal control problem, whose control variables are represented by the biomass quantity to be harvested, is formalized and solved through mathematical programming techniques. The novelties of the proposed EDSS regard the dynamical formalization of an optimal control problem for a sustainable use of the forest resources for energy production, the possibility of including different forest growth models (embedded as constraints in the optimization problem) and a carbon sequestration model as a function of the control and state variables, an accurate definition of forest felling and processing, primary transportation, and transportation costs, a constraint that limits the yearly harvesting to the biomass mean annual increment (calculated as function of the average age and of the control variables). The EDSS has been tested within the Val Bormida mountain community (Savona District, Liguria Region, Italy).

***Keywords**:* Renewable Energy, Forest growth, Optimization, Carbon balance, Environmental Decision Support System

1. INTRODUCTION

The use of renewable energy resources, as promoted by European Union, may represent the main alternative to avoid a further increase of carbon dioxide concentration in the atmosphere. Within the framework of the use of renewable resources for energy production, there is a growing interest towards forest biomass. However, the use of forest biomass requires a deep analysis, especially as regards to its environmental sustainability. This is due, first of all, to the necessity of harvesting in a sustainable way according to the forest vegetation growth. Attention should be also dedicated to the CO_2 emissions of the whole process. The development of optimal strategies that can guarantee the use of wood resources, satisfying the environmental constraints and controlling the forest growth, the carbon stock, and the CO_2 emissions seem to be a hard and important task in silvicultural practices. Different forest management systems affect the capability of forests to sequester carbon. In this framework, the use of forest growth models is very important for a successful woodland management. The last century has seen the development of the various forest models. However, despite the high potential of such models as management tools, only few of them seem to be suitable to be embedded in decision models for the forest management. Forest growth models generally applied as management can be classified, according to Gadow et al [2001] and Hasenaur [2006], within the following categories: a) highly aggregate volume-over-age models, used for regional yield forecasting; b) stand models used to predict the growth as a function of age; c) size class models used to predict the plants growth variations as regards the diameter distribution; d) individual tree models that provide information about the plant growth, on the basis of spatial relations. Forest growth models are necessary to understand carbon sequestration models. In fact, carbon assimilation and storage in the vegetal living tissues vary with the age of the plants and are strongly correlated with the increment of biomass (Masera [2001], Masera et al [2003]).

The general aim of this work is to define a decision model that can help in finding the optimal planning strategies over time for the sustainable use of forest biomass for energy production. These strategies ought to minimize costs and, at the same time, should guarantee the satisfaction of environmental constraints, the control of forest growth, the carbon stock and the CO_2 emissions. An optimal control problem has been formulated in which the control variables are represented by the quantity of forest biomass that is harvested in a specific time interval, while the state variables are the biomass quantity and the biomass average age. The decision model has been included in a GIS-based EDSS. The novelties of this paper with respect to other recent works (e.g. Freppaz et al. (2004)) regard the dynamical formalization of an optimal control problem for a sustainable use of the forest resources for energy production, the possibility of including different forest growth models (embedded as constraints in the optimization problem) and a carbon sequestration model as a function of the control and state variables, an accurate definition of forest felling and processing, primary transportation, and transportation costs, a constraint that limits the yearly harvesting to the biomass mean annual increment (calculated as function of the average age and of the control variables). Four different alternative forest growth models have been included: yield table, regional, stand, and matrix transitional models. For brevity, in the following sections, only the yield table model is described. The EDSS has been tested for the case study of Val Bormida (Savona district, Italy), for which the yield table model has been selected.

2. THE SYSTEM DESCRIPTION

The developed EDSS requires the information on the territory characteristics, the available biomass quantity, the plant size and location, the costs related to harvesting techniques associated to the different slope classes, the available roads, the forest growth models (and the related parameters) that can be used for the territory under concern. The EDSS outputs are the planning of the optimal harvesting over time, minimizing costs and guarantying good silvicultural practices. Moreover, other outputs regard the impact of the harvesting over the forest growth, and CO_2 emissions of the whole process, considering both emissions from technologies and uptake from the forest system. The main objectives of the present work is the use of forest growth models, with the aim of embedding them as constraints in the optimization problem formalization, and the quantifications of the carbon balance. In this section, the forest growth and carbon balance models are described in detail as a function of the control and state variables.

2.1 Modelling forest growth

The main features characterizing different forests are the species, the situ, the age, and the density. Forest growth is influenced by the above mentioned parameters and by their degree of homogeneity in a specific area. The spatial area for which the classification of forests is addressed varies on the basis of different factors, such as the degree of homogeneity, the available data, and the level of aggregation that can be (or has to be) pursued. A forest characterized by a high degree of homogeneity as regards the age of the plants is, in general, defined as *even-aged forest*. The whole population has the same silvicoltural phase and the same behaviour in time. On the contrary, a forest characterized by the presence of trees at different ages on the same territory is called *uneven-aged forest*. Forests can be further classified as *monospecific* if they are represented by only one species, or *mixed* forest if more species cohabit together. Independently of the degree of variability, forests can be composed by representative units. On the basis of such units, a model may be classified as a whole stand model or a single-tree model, which differ on the detail level of the information required and provided. A stand is defined as an area relatively homogeneous in terms of vegetation structure, growth dynamics, and species composition, and contains a number of trees for which a common set of characteristics can be created. Therefore, a stand is conveniently defined as a homogeneous unit of the forest and may be characterized by even-aged or uneven-aged structure. All models are constituted by empirical equations derived by interpolation of data sets and originally developed for silvicoltural management purposes. Forest models applied in the EDSS take into account the whole stand while single tree models are not considered. Specifically, four classes of forest growth models have been considered: yield table, regional, stand, and transition matrix models. In this paper, for brevity, attention is focused on the yield table model. Yield table models consider even-aged forest structure and are monospecific. They are represented by highly aggregated yield-over-age equations and are used, specifically, for predicting the development of a forest in response to a series of periodic harvesting levels. The yield table represents a simple and widely used aid in forestry practice and is used when the tables (or analogous curves or mathematical equations) are available for the specific site. They represent the growth of the whole stand in terms of height (mean and dominant), diameter (at human breast height), number of trees for hectare, basal area, total biomass and annual increment (mean and current), in function of the stand age. In this work, the mean annual increment, I_i^t (per unit surface), for each forest parcel i, i=1,… ,N and each time interval (t, t+1), t=0,…,T-1, has been used to describe the forest growth as a function of time. The values that are found in the yield tables are fitted by a mathematical relation between I_i^t, and the forest age, Age_i^t [year]. This relation expresses the current annual increment as an empirical function of the forest age and is represented by $I_i^t = f_i(Age_i^t)$, where, in this paper, the following structure for function $f_i(\cdot)$ has been adopted:

$$I_i^t = a_i (Age_i^t)^2 + b_i (Age_i^t) + c_i \qquad i = 1,\dots,N \qquad t = 0,\dots,T\text{-}1 \tag{1}$$

where a_i, b_i, c_i are species specific parameters (corresponding to the dominant specie in parcel i).

The biomass at the end of the time interval depends on the annual biomass increment, and on the amount of biomass collected during the same time interval on the whole parcel i, u_i^t [m^3]. Thus, for the proposed model, the state variable is the whole quantity of biomass v_i^t [m^3] at the beginning of time interval (t, t+1), while the control variable is represented by u_i^t [m^3] and refers to the amount of biomass collected in time interval (t, t+1). Moreover, it is necessary to take into account that, every year, only a part of the whole biomass present on the parcel is collected and that the increment of the biomass is age-dependent. The new biomass grows in a different way with respect to the ones that are not collected. After thinning, the total biomass is given by the sum of the one that is present in the different sub-parcels with different rates of growth. In this paper, the forest parcel i is considered *even-aged*, and average age is calculated in each parcel after the thinning operation. Thus, the average age Age_i^t can be updated as follows

$$Age_i^{t+1} = \frac{u_i^t}{v_i^t} + \left(Age_i^t + 1\right) \cdot \frac{v_i^t - u_i^t}{v_i^t} \qquad t=0,\dots,T\text{-}1 \qquad i=1,\dots,N \tag{2}$$

where $\frac{u_i^t}{v_i^t}$ is the fraction of the parcel that is harvested in time interval (t, t+1), and $\frac{v_i^t - u_i^t}{v_i^t}$ is the fraction of the parcel that is not harvested in time interval (t, t+1).

The forest growth state equation is expressed by:

$$v_i^{t+1} = v_i^t - u_i^t + I_i^t \cdot S_i \qquad t=0,\dots, T\text{-}1 \qquad i=1,\dots,N \tag{3}$$

where S_i is the forest parcel surface [ha].

2.2 Modelling carbon balance

The CO_2 balance model does not enter either the constraints or the objective of the optimization problem. However, it is important to express it as a function of the state and control variables in order to calculate the CO_2 emissions for the optimal solution. The general structure of the model follows the CO2FIX model (Masera [2001], Masera et al [2003]), as regards the quantification of carbon uptake or release. The model evaluates the net carbon release or uptake by the ecosystem with a step time of one year. The net annual carbon uptake or release, $NetCO_2^t$ [t CO_2 y^{-1}], is given by the difference between the carbon stored in wood, $CO_{2,stock}^t$ [t CO_2 y^{-1}], and the emissions due to biomass exploitation (transport, plant emissions, harvesting), $CO_{2,emis}^t$ [t CO_2 y^{-1}]. Both $CO_{2,stock}^t$ and $CO_{2,emis}^t$ are calculated as a function of the harvested biomass u_i^t. In the former case, the carbon stored in wood depends on the forest age that depends on u_i^t.

The CO_2 stored in the forest ecosystem, $CO_{2,stock,i}^t$ [t CO_2 y^{-1}], at time t in each forest parcel i, is given by the sum of carbon stored in the vegetation, Cv_i^t [t C y^{-1}] and the carbon stored in the wood products, Cp_i^t [t C y^{-1}]. To convert the amount of carbon into equivalent CO_2 absorbed, it is necessary to multiply for a conversion factor, K_{CO2}, that represents the ratio between the molecular weight of the CO_2 and of the carbon (equal to 44/12). Carbon in the living biomass, Cv^t, is determined as the sum of the carbon stored in each forest parcel i. Carbon stored in parcel i at time t, Cv_i^t, is calculated as the sum of the amount of carbon present in the parcel at the time t-1, $Cv_i^{(t-1)}$ [t C], plus the carbon stored by the biomass growth during the time interval (t-1, t), calculated as a function of the biomass annual increment I_i^t [m^3 ha^{-1} y^{-1}], minus the losses due to the harvest operations u_i^t [m^3 ha^{-1}]. The wood products represent a sink of carbon at different degree of release of CO_2 as function of the rate of degradation. Wood products kinds can be classified as long, medium and short term. Carbon in wood products is determined by the carbon content in the portion of biomass used for other destinations than the energy production, minus the share of the product that decomposes each year. The equations are omitted for brevity.

To evaluate the net amount of CO_2 released in the atmosphere from the whole biomass to energy supply chain, three major contribution should be taken into account: the carbon dioxide emissions from the conversion plant, CO_2fuel [t CO_2 y^{-1}], from the biomass transport, CO_2tr [t CO_2 y^{-1}], and from the forest operations, CO_2ha [t CO_2 y^{-1}].

The yearly emissions from the conversion plant depend on the amount of carbon in the fuel, Kc, and on the biomass quantity collected from each parcel i, u_i [m^3 y^{-1}]. These two parameters must be multiplied for a stechiometric ratio, K_{CO_2} (44/12), to obtain the amount of CO_2 released in the atmosphere, and for the parcel surface, S_i (ha). The yearly emissions from transport depend on the quantity of transported biomass. The transport emissions are divided in two phases, the emission deriving from the primary transportation, $CO2pt^t$ [t CO_2 y^{-1}], from the forest to a point near the first road (landing point), and the secondary transportation, $CO2sp^t$ (t CO_2 y^{-1}), from the landing point to the plant. Emissions during primary transportation phase are determined on the basis of the primary transportation system used, that is associated to the acclivity j (j = 1, …, J), and to the total distance from the parcel centroid to the landing points. For each type of primary transportation system, a specific efficiency is assigned on the basis of the fuel consume, $E_{j,pt}$ (km l^{-1} fuel). Moreover, for each system, the number of times that a forest vehicle employs to transport the biomass collected from the felling point to the nearest road is determined. Such parameter is determined on the basis of the amount of biomass collected from each parcel i, u_i (m^3 y^{-1}), and the forest vehicle capacity (vV_j). Emissions during secondary transportation phase are determined on the basis of the number of times employed by a vehicle, the distance to the plant, and the vehicles fuel consumption. Finally, CO_2 production from forest operations is expressed as a function of the amount of CO_2 emitted per m^3 of biomass cut by chainsaw, and of the harvested biomass. For brevity, equations are not reported here.

3. FORMALIZATION OF THE DECISION PROBLEM

3.1 The decision problem description

The main objective of this paper is to define a decision model able to determine the quantity of forest biomass to be harvested over time in a specific territory, in order to satisfy the material request from a biomass conversion plant and to guarantee a sustainable use of the forest resources. Specifically, great attention is focused on the forest system and on the definition of state equations, embedded as constraints in the optimization problem. In the following, an explicit formalization has been provided for the yield table model. The forest system is subdivided into a set of i-th parcels, $i = 1,.....,N$, defined on the territory on the basis of a homogeneous vegetation type. Each parcel i is moreover subdivided in sub-parcels in base of the specific acclivity. Five slope classes j, $j = 1,.....,J$, have been considered. The objective function includes costs related to the trees harvesting and transport. Two different forest operations, the felling and processing phase, and the primary transportation phase, according also to the area acclivity, have been considered. The felling and processing phase, FP , only regards operations executed by chainsaw, while the harvester and the processor are not taken into account. The felling process regards the biomass cutting phase, without with no other treatment or process. The processing phase (whose productivity is indicated as $\Pr^{FP}$ [m^3 h^{-1}]) regards the first phase of trees pre-treatment and it is constituted by three independent operations: the delimbing (Del), the debarking (Deb) and the cross cutting (Cc). Delimbing consists of removing the barks from the trees, debarking is the elimination of branches while cross cutting is the stem cutting in smaller parts. On the basis of many factors, like the territory configuration or the primary transportation techniques, one or more of these operations can be neglected. The absence of an operation causes the increase/decrease of the productivity and in particular of the overall time to perform the various operations. To model this possibility for each of these a reduction factor for the operation time, T [%], is found. A binary parameter δ for each possible operation allows to exclude one or more forest operations with the consequential improvement of the productivity and the reduction of the unit cost, C_U^{FP} [€ h^{-1}]. The forest primary transportation, FT , is the transport from the felling areas to the landing points near the first available road. The transportation technique mainly depends on the j-th slope class of the sub-parcel. For the sake of simplicity, the most suitable primary transportation technique is defined for a j-th class and consequently for each sub-parcel, choosing among sliding, skidding, trailer, yarder and chute. For each technique a certain productivity value, $\Pr_{i,j}^{FT}$ [m^3 h^{-1}], and unit cost, C_j^{FT} [€ h^{-1}] are established. The productivity value decreases with the increasing of the distance, d_i^{FL} [km], from the felling areas to the landing points, following the course of a decreasing monotonic continuous function specific for each transportation technique. The dependence of the monotonic function from the transportation technique is expressed from the numerical parameter p_j and m_j , evaluated from the fitting of bibliographical values. The forest primary transportation cost for each parcel is then obtained as the average sum of the costs of the j-th parcels. Instead, the biomass transportation includes the transport from the landing points to the plant or warehouse location. This cost is strongly dependent on the distance, d_{SP_j} , on the biomass quantity that must be transferred, and on a unit cost for transport, C_U^T [€ kg^{-1} km^{-1}].

3.2 The control and state variables

In this work, the control variables are represented by, u_i^t that correspond to the yearly amount of biomass harvested from the *i-th* parcel [m^3 y^{-1}]. The state variables, necessary to represent the system state, are the amount of biomass, v_i^t [m^3], present in each parcel at a specific time t, and the average age of a forest parcel Age_i^t [y].

3.3 The objective function

The objective function is composed by three different cost; the cost of forest biomasses felling and processing, C_{FP} [€ y^{-1}], the cost of forest biomasses primary transportation C_{FT} [€ y^{-1}] and the transportation cost from the landing points to the plant, C_T [€ y^{-1}]. That is,

$$C = C_{FP} + C_{FT} + C_T \tag{4}$$

with

$$C_{FP} = \sum_{t=1}^{T}\sum_{i=1}^{N} C_U^{FP} \frac{u_i^t}{\Pr^{FP}}\left(1 - T_{Del}\delta_{Del} - T_{Deb}\delta_{Deb} - T_{Cc}\delta_{Cc}\right) \tag{5}$$

$$C_{FT} = \sum_{t=1}^{T-1}\sum_{i=1}^{N} u_i^t \sum_{j=1}^{J} \frac{C_j^{FT}}{\Pr_j^{FT}\left[1 - \left(1 - Exp^{\left(-m_j d_i^{FL}\right)}\right)^{p_j}\right]} \tag{6}$$

$$C_T = \sum_{t=0}^{T-1}\sum_{i=1}^{N} d_{SP,i}\, u_i^t\, VM_i\, C_U^T \tag{7}$$

where VM_i is the volumetric mass for forest parcel i.

3.4 The constraints

Three classes of constraints have been formalized: the biomass growth state equation, described in section 2.1 (see (1), (2) and (3)), the restrictions over the biomass use, and the plant energy balance. As regards the constraints over biomass use, two kinds of constraints are formalized: thresholds imposed by regulation, and thresholds suggested by good silvicoltural practices. In the former case, a coefficient imposes to harvest just a fraction of the available biomass. In the latter case, it is imposed that it is not possible to harvest more than the total annual increment of biomass in each parcel. As regards regulation limits, the constraints for the generic time interval (t, t+1) are:

$$u_i^t \le \alpha_i v_i^0 \qquad i=1,\ldots,N;\ t=0,\ldots,T-1 \tag{8}$$

$$u_i^t \le \alpha_i v_i^t \qquad i=1,\ldots,N;\ t=0,\ldots,T-1 \tag{9}$$

where α_i is a species-specific parameter.

As regards silvicoltural good practices, it is possible to introduce a constraint on the amount of biomass annually harvested to determine a sustainable forest exploitation. Such constraint determines that the annual biomass collection, u_i^t, should be lower or, at maximum, equal to the mean annual increment, I_i^t, for the parcels that have average age $Age_i^t \le Age_i^{\max}$, and to the maximum increment I_i^{max}, otherwise. That is,

$$u_i^t \le \begin{cases} I_i^t & if \quad Age_i^t \le Age_i^{\max} \\ I_i^{\max} & if \quad Age_i^t > Age_i^{\max} \end{cases} \qquad i=1,\ldots,N;\ t=0,\ldots,T-1 \tag{10}$$

For a yield table forest growth model this means

$$u_i^t \le (a_i\left(\min\{\ Age_i^t, Age_i^{\max}\ \}\right)^2 + b_i\left(\min\{\ Age_i^t, Age_i^{\max}\ \}\right) + c\ )S_i$$

i=1,…,N t=0,…,T-1 (11)

The third class of constraints regards the energy balance at the conversion plant. As regards production plant constraints, the plant is supposed to operate at the maximum productivity level. The following equation states that the plant capacity *HVP* should be equal to the power developed by the conversion of the biomass entering the plant. That is,

$$HVP = \sum_i LHV_i \left(u_i^t VM_i \; f \right) \tag{12}$$

where $f = \dfrac{1}{3600\,h}$ is the conversion factor to transform thermal energy [MWh] in power [MW], with 3600 the number of seconds in an hour, and LHV_i is the low heating value.

4. APPLICATION TO A CASE STUDY

The EDSS has been tested within the Val Bormida mountain community (Savona District, Liguria Region, Italy). The study area includes 18 municipalities and the territory is characterized by a high forest density: it is covered by forests for the 75% of the total valley surface. Excluding the parts of the forest territory that can not be exploited for the presence of legislative constrains (natural parks and protected areas), for the occurrence of forest fires and hydro-geological disasters, for the presence of great bio-naturalistic importance areas, the total study area is about 28000 hectares. Such surface has been divided in 506 forest parcels that correspond to a specific homogeneous vegetation type as indicated by the forest map of the Liguria Region. Therefore, each parcel is characterized by one main typology of biomass out of five typologies of biomass (beech, chestnut, conifer, hardwood and softwood) located in various parts of the territory. Forest parcels have been divided into five classes of acclivity for the determination of forest operation costs. Biomass transport and energy production costs have been calculated too. The application of the EDSS in the territory of Val Bormida allowed determining the optimal harvesting management over time for a known plant capacity. A receding-horizon control scheme has been adopted. Moreover, a sensitivity analysis as regards different plant capacities (*HVP* = 3, 4, 5, 6 MWe) has been performed. For each plant capacity, the effects of different biomass collection levels on forest growth and on the potential carbon sequestration by vegetation are evaluated. In Table 1, the results of the optimization problem have been reported, for a time horizon of 15 years and for the different plant capacities.

Table 1. The results of the optimization problem

Cap [MWh]	**3**	**4**	**5**	**6**
Average harvesting biomass [m^3]	59606	79880	99345	119211
Yearly cost [€]	1.572.617	2.247.856	3.045.621	3.985.500
Yearly average cost [€ m^{-3}]	26,38	28,14	30,66	33,43
Total electrical energy [MW]	24 10^3	32 10^3	40 10^3	48 10^3
Used parcel	228	311	372	428
% on total biomass	0,58%	0,77%	0,96%	1,15%

An interesting analysis is to compare vegetation growth and CO2 balance in the optimal solution under different levels of biomass collection (that obviously correspond to the different plant capacities (3, 4, 6 MWe)). In Figure 1, the CO2 balance for the three plant sizes, is shown: the CO2 balance is never negative.

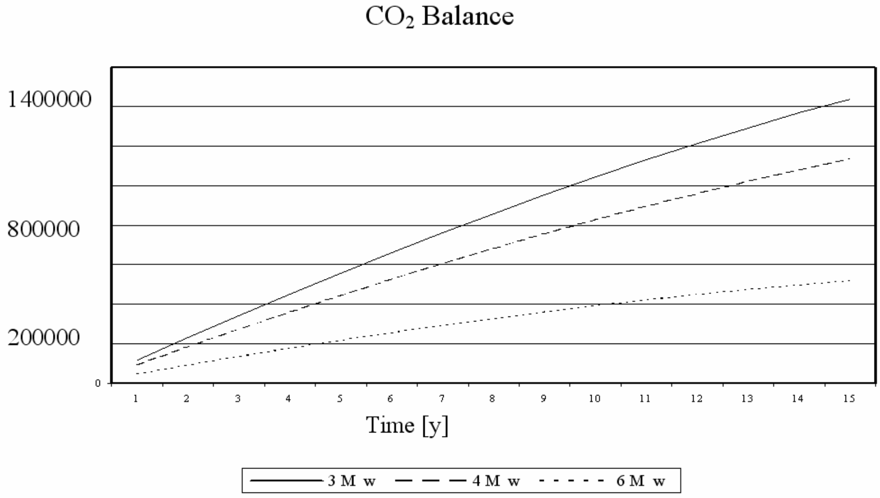

Figure 1. The carbon-dioxide balance

5. CONCLUSION

A decision model for the planning of forest biomass use for energy production has been described. Attention has been focused on the forest system in order to take into account sustainable silvicultural practices and the CO_2 balance that characterizes the biomass supply chain. The optimization problem has been solved for the case study of Val Bormida (Savona district, Italy), for which the yield table model has been selected. A sensitivity analysis as regards different plant capacities has been performed. The effects of different biomass collection levels on forest growth and on the potential carbon sequestration by vegetation are evaluated. The novelties of the proposed decision model regard the dynamical formalization of an optimal control problem for a sustainable use of the forest resources for energy production, the possibility of including different forest growth models (embedded as constraints in the optimization problem) and a carbon sequestration model as a function of the control and state variables, an accurate definition of forest felling and processing, primary transportation, and transportation costs, a constraint that limits the yearly harvesting to the biomass mean annual increment (calculated as function of the average age and of the control variables). Future developments of the proposed work regard, first of all, a more detailed characterization of the forest parcels, according to the slope and the available roads. Then, satellite data can be used in order to compare collected data for the forest system over the whole territory. As regards plant technologies, results have been found for combustion but can easily found for other plant typologies (pirolysis, gasification). Finally, a more detailed schedule of the forest primary transportation operation among parcels might be performed.

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