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Carbon captured as a new instrument in forest management: some implications

Captura de carbono como um novo instrumento para o manejo florestal: algumas implicações

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ABSTRACT: The recent consideration of forest ecosystems as possible sinks of carbon dioxide (CO_2) makes necessary its inclusion in the forest management models. This type of inclusion generates theoretical changes in the system of calculation of the rotation ages. In this sense, it is interesting to research if the current forest policies encouraging afforestation programmes "push the forest owner" towards rotation ages that optimises the capture of CO_2. It is also interesting to note that the consideration of this new objective implies important changes in the traditional methods of forest management based upon exclusively in timber production. The main objective of this work is to check if several forest management frameworks (rotation age, harvest scheduling) modify their values when carbon captured is included into the management process. After reviewing the above topics, some new methods based on goal programming are proposed. This type of approach allows the determination of harvest schedules that represent sensible and robust compromises between economic timber returns and the CO_2 captured.

KEYWORDS: Carbon sinks, Forest management, Forest economics

RESUMO: A recente consideração de ecossistemas florestais como alternativas elegíveis para o seqüestro de dióxido de carbono (CO_2) torna necessária a sua inclusão em modelos de manejo florestal. Esse tipo de inclusão gera mudanças teóricas nos sistemas de cálculo das idades de rotação. Nesse sentido, é interessante investigar se as atuais políticas florestais que encorajam os programas de florestamento incentivam o proprietário florestal a adotar rotações que otimizam a captura de CO_2. Também é interessante notar que a consideração deste novo objetivo implica em importantes mudanças nos métodos tradicionais de manejo florestal voltados exclusivamente para a produção de madeira. O objetivo principal deste trabalho é confirmar se vários modelos de manejo florestal (envolvendo escolha de rotações e agendamento de colheitas) modificam os seus resultados ao se considerar regimes que seqüestram carbono. Após a revisão dos tópicos acima, alguns métodos baseados em programação por metas são propostos. Este tipo de abordagem permite a determinação de programas de colheitas que representam compromissos sensíveis e robustos entre os retornos econômicos e a captura de CO_2.

PALAVRAS-CHAVE: Seqüestro de carbono, Manejo florestal, Economia florestal

INTRODUCTION

In the last few years some international principles of agreements like Kyoto Protocol have been outlined in order to reduce the atmospheric emissions of certain gases. The reason underlying these agreements is the crucial importance of taken measures facing a possible global climatic change.

From the forestry point of view, it is important to be aware that the Kyoto Protocol explicitly considers ARD (afforestation, reforestation and deforestation) activities in order to account the carbon captured; i.e., the forest ecological function as CO_2 sinks is totally considered in the protocol as a measure to mitigate this problem. It is rather obvious that the final balance will be positive or negative depending upon the evolution of the afforestation and deforestation rates since 1990. In order to account properly the carbon it is considered not only the carbon stored in the commercial parts of the tree but also the carbon stored in the soil, leaves, branches etc. Even some interpretations of the article 3.4 of the Kyoto Protocol might allow the consideration of the carbon accumulated in products derived from timber as the carbon captured for the growth of the current stands (Nabuurs et al., 2000).

Nevertheless, despite the inclusion of this objective in the Spanish and European forest policy strategies, the current management mechanisms do not consider its inclusion. Thus, at a stand level the usual procedures to calculate the optimal rotation are not applicable when the carbon captured is considered. Within this line some works have attempted to adapt the Faustmann approach to a context where the CO_2 captured is considered (Hoen, 1994; Van Kooten et al., 1995; Romero et al., 1998).

On the other hand, if forest management focuses at a forest level, then is necessary to incorporate directly this objective into the strategic planning. One example in this direction is the work by Hoen and Solberg (1994), where a bi-objective function, with net present value and CO_2 captured as arguments, is introduced.

In this paper, the carbon captured will be considered as an explicit management objective at a stand level as well as a at forest level. After analysing the effect of carbon captured on the optimal rotation age of plantations, then the other objectives considered are the following: to study the effect of the consideration of the carbon captured in afforestation programs in species of short rotation (*Populus* sp.) and medium rotation (*Pinus radiata*), as well as to test the results obtained when this new criteria is introduced on strategic forest planning models. Moreover, the main results derived from a forest management model with multiple criteria to a forest covered with a long rotation species (*Pinus sylvestris*) in Spain will be presented.

METHODOLOGY

In order to include the carbon captured some previous considerations should be made. First, it is necessary to define the form chosen for measuring the increment in the carbon captured. Thus, we have the carbon accumulated in the trees due to their growth process (gross carbon). This type of carbon is the easiest to measure. The second form is related with the efficiency in the process of carbon accumulation. Thus, if it is encouraged that the final use of timber will be products with a long life, then the re-emission of CO_2 to the atmosphere will be very slow. In other words, in this case what is measured is not gross carbon but net carbon, that is calculated as the difference between the carbon captured by the biomass and the carbon emitted according to the different uses of the timber harvested.

The above considerations imply that the election of the forest rotation is a basic decision for two reasons. First, because the rotation chosen can increase the total carbon captured. Second, the cutting age influences the suitability of the products for a potential reallocation of carbon from forests to other sources and sinks.

In order to estimate the forest carbon content, it has been assessed the carbon to be captured each year, including the carbon due to the biomass growth as well as the carbon retained in the products from timber derived from thinning operations and from regeneration harvests. To achieve this purpose three types of uses for timber are considered: veneer, sawtimber and engineered wood composite. A possible use for pulp is not considered as well as a possible re-utilisation by a recycling process. The calculation of the carbon captured, for each different timber use, is made by accepting the working hypothesis stated by Row and Phelps (1996).

Finally, the usual way to fix a price to the carbon captured consists in the determination of the willingness to pay by the society for a ton of CO_2 captured. However, in this paper we have considered the price as the subsidy that makes equal the private and the social optimum.

Forest plantations

To undertake this analysis we have considered the usual methodology for the determination of the economic optimum forest rotation. From a financial perspective it is well accepted that the correct procedures is the one proposed by Faustmann (1849). This methodology defines the optimum rotation as the life of the stand for which the net present value of the underlying investment achieves a maximum value, taking into account the land rent. In order to apply properly the Faustmann formula to our context the procedure suggested by Díaz Balteiro and Romero (1995) and Mutke et al. (2000) has been followed. Thus, a sales revenue function $I(t) = p \cdot f(t)$ is introduced, being p the timber price and $f(t)$ the growth curve. K represents the plantation costs, G the general annual management payments, Y_S the cultural operations and C_l the receipts derived from thinning operations.

Besides the above payments and receipts it is also necessary to introduce the financial subsidies provided by the current European forestry policy. These types of financial aids have considerably encouraged new plantations in the last few years (Herruzo, 2001). In this sense there are three categories of aids. A maintenance premium P_m received during the first five years of the plantation cycle; a compensatory premium P_c received during the first twenty years of the plantation cycle and a subsidy K_1 to mitigate afforestation costs. Taking into account all these components, and being aware that the different subsidies are perceived only in first plantation cycle, the Net Present Value (NPV) attached to the investment will be equal to:

$$NPV = \frac{I(t) \cdot e^{-i \cdot t} - K - G \cdot a - \sum_{\forall s} Y_s \cdot e^{-i \cdot s} + \sum_{\forall l} C_l \cdot e^{-i \cdot l}}{1 - e^{-i \cdot t}} + K_1 + P_m \cdot b + P_c \cdot g$$

with:

$$a = \frac{e^{(-i \cdot 1)} \cdot (e^{(-i \cdot t)} - 1)}{(e^{(-i \cdot 1)} - 1)} \qquad (1)$$

$$b = \frac{e^{(-i \cdot 1)} \cdot (e^{(-i \cdot 5)} - 1)}{(e^{(-i \cdot 1)} - 1)}$$

$$g = \frac{e^{(-i \cdot 1)} \cdot (e^{(-i \cdot 20)} - 1)}{(e^{(-i \cdot 1)} - 1)}$$

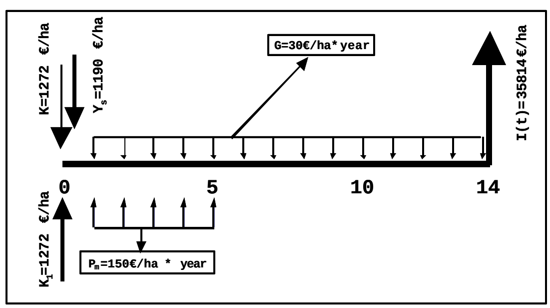

Figure 1
Diagrammatic presentation of the investment process (*Populus* sp.)
(Representação gráfica do processo de investimento (*Populus* sp.))

A diagrammatic presentation of the investment process was included in Figure 1. The optimal forest rotation as well as the profitability of the different plantations is obtained by maximising expression (1). However, when we are considering a joint production process timber-carbon captured, the above procedure is not applicable. Even the extension of Faustmann formula introduced by Hartman (1976) is neither applicable since this approach requires the estimation of a flow of services measured in monetary terms. To circumvent this problem we have followed in this paper a methodology proposed by Romero et al. (1998). With this purpose in mind a subsidy A (€ per ton of carbon captured) will be introduced. In the same way, a tax of A will be levied for each ton of carbon emitted to the atmosphere. Taking into account this new context equation (1) turns into:

$$NPV = \frac{I(t)\cdot e^{-i\cdot t} - K - G\cdot a - \sum_{\forall s} Y_s \cdot e^{-i\cdot s} + \sum_{\forall l} C_l \cdot e^{-i\cdot l} + A\sum_{\forall r} C_a \cdot e^{-ir} - A\sum_{\forall v} C_e \cdot e^{-iv}}{1-e^{-i\cdot t}} + K_1 + P_m \cdot b + P_c \cdot g \quad (2)$$

with:

$$a = \frac{e^{(-i\cdot 1)}\cdot(e^{(-i\cdot t)}-1)}{(e^{(-i\cdot 1)}-1)}$$

$$b = \frac{e^{(-i\cdot 1)}\cdot(e^{(-i\cdot 5)}-1)}{(e^{(-i\cdot 1)}-1)}$$

$$g = \frac{e^{(-i\cdot 1)}\cdot(e^{(-i\cdot 20)}-1)}{(e^{(-i\cdot 1)}-1)}$$

Where C_a (ton C/ha) represents the carbon captured when the age of the stand is r. C_e represents the carbon emitted in the year v. It should be noted that we have only considered the carbon stored in the marketable timber in the final cut as well as in the thinnings. However, we have not considered the carbon captured in other type of biomass nor the variation of carbon in the soil. The discount rate chosen is 7% and no taxes will be considered.

In all the cases studied the NPV, the optimal forest rotation as well as the amount of carbon captured will be calculated for the private optimum (corresponds to the Faustmann optimum) and the environmental optimum (corresponds to the maximum capture of carbon). Although some exceptions are cited in the literature (Rodriguez et al., 1997) the longest rotation corresponds to the environmental optimum and the shortest rotation to the economic optimum.

Permanent stands

Traditionally the primary objective of forest management in Spain and in other European countries has consisted in achieving certain timber volume targets. However, in the last few years new objectives have been incorporated in the management of the forest, and the traditional European forest management methodologies can only deal with timber objectives. For this reason is completely necessary to resort to the tools of the Operational Research discipline in order to incorporate several objectives in the forest management planning.

Consequently, the multi-criteria methodology known as Goal Programming will be used to tackle this type of problem. The first step in our work will consist in defining the different goals considered in this type of problem. Thus, we have considered an economic goal (to minimise the negative deviation with respect to the maximum NPV). Moreover, three forestry goals have also been considered to minimise the unwanted deviations with respect to an even-flow policy: obtaining a regulated forest and securing a satisfactory final inventory. Finally, an environmental goal has been considered. This goal minimises the unwanted deviations with respect to the maximum carbon captured by the forest along the planning horizon considered (100 years).

Once the different goals have been defined, the achievement function minimising the unwanted deviation variables is introduced. In order to minimise the achievement function subjected to the corresponding constraints, two Lexicographic Goal Programming models have been used. The technical details about these models can be found in Díaz-Balteiro and Romero (2003). Basically, both lexicographic models grouped the goals into three priority levels. The first priority level corresponds to the goal that secures a satisfactory final inventory. The second priority level includes the goal corresponding to the regulation condition. The last priority level includes the other three goals corresponding to the NPV, the even-flow policy and the carbon captured. In the first model the weighted and normalised sum of unwanted deviation variables is minimised while in the second model the maximum deviation is minimised. Technical aspects as well as the rationale underlying to this type of optimisation approaches can be seen in Romero (1991) and Ignizio and Cavalier (1994).

RESULTS

We are going to present separately the results corresponding to plantations with respect to the results corresponding to permanent stands.In the Annex 1 appear the main characteristics of the afforestation program considered, while in the Annex 2 the basic aspects of the forest analysed are presented.

Annex 1
Characteristics of the afforestations with *Populus* sp. and *Pinus radiata*.
(Características de florestamentos com *Populus* sp. e *Pinus radiata*)

		***Populus* sp.**	***Pinus radiata***
afforestation cost		1,272 €/ha	1,563 €/ha
annual cost		30 €/ha*year	12 €/ha*year
cultural operations costs*		1,190 €/ha	1,966 €/ha
European aids	K_1	1,272 €/ha	1,266 €/ha
	P_m	150 €/ha	180 €/ha
	P_c	0 €/ha	166 €/ha
volume obtained at private optimum		356 m^3	377 m^3
Thinnings		no	yes
timber price		60-68 €/m^3	51 €/m^3

*discounted to zero year

Annex 2
Main characteristics of the "Pinar de Navafria" forest and management
(Principais características florestais e de manejo do "Pinar de Navafria")

area asigned to each site index

site index	**Site I**	**Site II**	**Site III**	**Site IV**	**Site V**
area (ha)	754,85	426,53	771,38	444,86	105,25

area asigned to each age class

age class	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**100**	**110**	**120**	**130**	**150**
area (ha)	42,37	347,16	133,44	355,82	58,4	356,81	230,11	49,56	352,71	139,2	392,06	46,73

Planning horizon:	100 years
time unit	10 years
interval final age class	20 years

discount rate	0,02
maintenance cost	24 €/ha*year
timber price	71,4-94,7 €/m^3

Forest plantations

Let us start with the case of poplar plantations without considering any type of subsidy. Within this context the optimal forest rotation is 14 years, corresponding a NPV around 17,000 €/ha. For this type of private optimum the gross carbon captured is around 44.7 ton C/ha. Within an environment of financial subsidies the forest rotation raises up to 15 years, due to the possibility of receiving the maintenance premium. In this new context the profitability increases a little, achieving a NPV per hectare of 18,243 €. The increase in the forest rotation produces a tiny increase in the carbon captured of 49.24 ton C/ha.

On the other hand, the environmental optimum implies a forest rotation of 18 years, providing a maximum carbon captured of 56.95 ton C/ha. However, if we consider a cycle of plantations the optimum will not correspond to this maximum age but to the age for which the average carbon captured reaches a maximum value. This age is 17 years with a carbon capture of 55.02 ton/ha. For this rotation the NPV achieves the figure of 14,246 €/ha without subsidies and of 16,132 €/ha when the European aids are considered. In other words, to enlarge the forest rotation up to this age implies to give up the 16% of the NPV when there are not subsidies and the 12% in a context of financial aids. If we consider the net carbon instead of the gross carbon, this optimum does not alter. Thus, the net carbon has been calculated by accepting the above stated hypothesis and by assuming that all the stored carbon is re-emitted to the atmosphere after 150 years. The figures obtained for the net carbon oscillate between the 15% and the 20% of the gross carbon after 200 years of plantation. Table 1 shows the gross and the net carbon according to the afforestations considered. Table 2 shows the results obtained in terms of profitability.

Table 1
Balance of gross and net accumulated carbon in 100, 120, 150 y 180 years, in 2 species: *Populus* sp. and *Pinus radiata*.
(Balanço do acúmulo bruto e líquido de carbono em 100, 120, 150 e 180 anos de duas espécies, *Populus* sp. e *Pinus radiata.*)

***Populus* sp.**	**GROSS CARBON (tm/ha)**				**NET CARBON (tm/ha)**			
Rotation	**100 years**	**120 years**	**150 years**	**200 years**	**100 years**	**120 years**	**150 years**	**200 years**
18	308,12	376,20	460,92	626,44	111,33	119,26	106,85	112,19
17	328,03	388,85	488,64	648,89	129,04	118,52	130,39	128,02
16	317,35	382,22	479,88	645,85	106,01	109,55	108,35	110,98
15	318,81	393,91	492,39	642,79	111,01	116,76	118,12	106,69
14	313,39	371,29	471,08	627,77	100,77	100,32	106,98	99,74
13	297,60	359,55	448,28	601,94	92,45	89,54	93,36	90,18
12	277,06	345,09	419,44	565,27	77,02	88,38	80,06	83,47
Pinus radiata	**GROSS CARBON (tm/ha)**				**NET CARBON (tm/ha)**			
Rotation	**100 years**	**120 years**	**150 years**	**200 years**	**100 years**	**120 years**	**150 years**	**200 years**
40	314,99	388,71	493,74	647,85	94,73	107,26	120,32	110,89
37	339,56	386,92	505,55	662,76	111,41	95,75	110,99	102,07
35	349,16	397,00	498,74	692,12	115,61	92,00	94,90	117,92
33	348,63	409,72	510,36	697,27	100,56	96,05	96,03	105,22
32	338,34	415,06	517,45	681,24	87,77	101,39	96,85	85,18
31	329,33	418,76	522,96	680,52	76,75	101,85	100,36	82,61
30	325,59	420,14	525,17	686,06	68,98	88,95	89,08	78,42
28	325,15	390,44	492,66	674,77	74,41	74,05	74,12	83,03
25	326,16	381,75	489,25	652,33	75,30	72,11	78,38	78,73

Table 2
Profitability taking into account a subsidy per ton of carbon captured of 25€/ton, in two afforestation programs: *Populus* sp. and *Pinus radiata*.
(Rentabilidade considerando-se um subsídio de 25?/ton de carbono seqüestrado, em dois programas: *Populus* sp. e *Pinus radiata*)

***Populus* sp.**	**NPV without afforestation grants [€/ha]**			**NPV with afforestation grants [€/ha]**		
Rotation	**NPV, no C**	**NPV + gross C**	**NPV + net C**	**NPV, no C**	**NPV + gross C**	**NPV + net C**
18	12.493	13.057	12.785	14.379	14.943	14.671
17	14.246	14.848	14.555	16.132	16.734	16.441
16	15.612	16.250	15.937	17.498	18.136	17.823
15	16.537	17.200	16.872	18.423	19.086	18.758
14	16.968	17.641	17.296	18.243	18.915	18.571
13	16.889	17.562	17.205	18.163	18.836	18.479
12	16.215	16.870	16.511	17.489	18.144	17.785
Pinus radiata	**NPV without afforestation grants [€/ha]**			**NPV with afforestation grants [€/ha]**		
Rotation	**NPV, no C**	**NPV + gross C**	**NPV + net C**	**NPV, no C**	**NPV + gross C**	**NPV + net C**
40	-1.358	-1.228	-1.147	2.488	2.618	2.562
39	-1.301	-1.164	-1.082	2.545	2.682	2.627
38	-1.244	-1.098	-1.017	2.602	2.748	2.692
37	-1.186	-1.033	-950	2.661	2.813	2.759
36	-1.128	-968	-884	2.718	2.878	2.825
35	-1.073	-905	-820	2.773	2.941	2.888
34	-1.021	-845	-760	2.825	3.001	2.949
33	-974	-791	-703	2.872	3.055	3.005
32	-934	-742	-654	2.912	3.104	3.055
31	-902	-703	-612	2.944	3.143	3.097
30	-881	-630	-581	2.965	3.216	3.128
29	-1.086	-872	-809	2.760	2.974	2.900
28	-1.096	-874	-810	2.750	2.972	2.899
27	-1.124	-895	-828	2.722	2.951	2.881
26	-1.173	-938	-870	2.673	2.908	2.839
25	-1.247	-944	-935	2.599	2.902	2.774

As it was commented above, to circumvent the difference between the private and the environmental optimum a subsidy ranging between 20 and 220 € per ton of carbon captured has been used. It is assumed that the forest owner maximises the sales revenue of the joint production using the same discount rate. The results obtained clearly show how the figure of forest rotation obtained is the same when gross or net carbon is considered. The subsidies do not increase the capture of carbon but increases considerable the private profitability. In fact, the NPV increase in a 27% if the gross carbon is considered with a subsidy of 200 €/ton.

It is interesting to note that the results obtained are rather inelastic to changes in the discount rate. This inelasticity is remarkable when subsidies are considered. Thus, for discount rates changing between 4-8%, the rotation age does not vary. When the discount rate achieves the 9%, the rotation age reduces to 13 years, increasing the gap with respect to the environmental optimum. For this discount rate, the consideration of subsidies increases the rotation age up to 15 years, Moreover, for a discount rate of 10% both rotation ages (with and without subsidies) coincides in 13 years.

For *Pinus radiata* plantations and within a scenario without subsidies this type of plantation is not financially viable. In fact, for an optimum forest rotation of 30 years a NPV of -881 €/ha is obtained (see Table 2). The consideration of subsidies does not influence in the rotation age but allows the achievement of a positive NPV of 2,965 €/ha. For this private optimum a capture of gross carbon of 105.03 ton/ha is obtained. In this case, it is important to note the importance of the sales revenue provided by the thinning operations. This type of revenue represents the 16% of the NPV when the subsidies are considered.

For the site index considered and taking into account the growth curve previously introduced, the rotation age providing the maximum sustainable yield achieves the figure of 33 years. To enlarge the rotation up to this age implies, *ceteris paribus*, to reduce the NPV in a 15% without subsidies and around 5% in a context of subsidies. This rotation age corresponds to the environmental optimum, providing a gross carbon captured of 116.21 ton /ha. In terms of net carbon, if the period of time considered is long (200 years), then the figure obtained is rather similar with respect to the poplar plantations.

If we try to mitigate the divergence between both optima through an increase in the subsidy the rotation age does not change. The increase in the subsidy once a certain threshold is surpassed can make the investment profitable considering only the gross carbon and without the European financial aids. Thus, a subsidy of 90 €/ton C implies that the NPV referred to the gross carbon reaches the figure of 24 €/ha. It is interesting to note that these results are robust to changes in the discount rate.

Permanent stands

Let us start obtaining the pay-off matrix. This is a square matrix with dimension equal to the number of goals considered (five in our application). The different rows of the matrix show the results obtained when each goal is optimised separately. See Table 3 for the results of our particular case. The main interest of this table consists in the information provided about the degree of conflict between the different goals considered. Thus, from Table 3 is easy to deduce that there is an important degree of conflict between the capture of carbon and the other goals considered. In fact, the capture of carbon is clearly less (it reduces nearly to one third) when the even-flow goal holds. Similar results are obtained when the forest regulation goal holds or when the goal related to the final forest inventory is met. On the contrary, the solution providing the maximum capture of carbon (see last column of Table 2) implies the worst results with respect to the other goals. Finally, in order to increase the informative character of this matrix two additional rows have been added to inform about the total harvest volume and the average rotation that corresponds to each goal.

The different solutions provided by the pay-off matrix do not seem enough attractive from a managerial point of view. For this reason, the Lexicographic Goal Programming models outlined above have been applied in order to obtain satisficing or best-compromise solutions. It is interesting to note that a sensitivity analysis with the preferential weights has been implemented. The different results obtained are shown in Table 4.

The main information derived from Table 4 can be summarised as follows. The goals placed in the first two priority levels are fully achieved in all the scenarios considered. In other words, in all the solutions obtained the goals related to the forest regulation and the final inventory completely achieved the aspiration levels established. On the contrary, for the goals placed in the third priority level there are deviations with respect to the corresponding aspiration levels.

Table 3
Pay-off matrix for the five criteria considered
(Matriz de pagamentos dos cinco critérios considerados)

	Net Present Value [NPV] nNpv	**Volume Control niH+piH**	**Area Control nif+pif**	**Ending Forest Inventory nkl+pkl**	**Carbon Balance nCB**
NPV (*10^6 €)	35,08	26,98	25,02	28,22	25,36
nNpv	0	8,10	10,06	6,86	9,72
niH+piH	1.051.803	0	0	43.359	589.471
nif+pif	2.133	442	0	293	3.080
nkl+pkl	286.833	35.305	6.048	0	413.824
Carbon Balance (Tm)	49.887	55.365	60.761	58.585	101.470
nCB	51.583	46.105	40.709	42.885	0
Volume (m^3)	1.298.536	1.018.108	966.115	1.008.948	609.812
Average Rotation	99	114	113	108	104

nNPV negative deviation variable for the net present value criterion (*10^6 €)
niH+piH: negative and positive deviation variables for the volume control goal (m^3)
nif+pif: negative and positive deviation variables for the area control goal (ha)
nkl+pkl: negative and positive deviation variables for the ending forest inventory goal (m^3)
Carbon Balance: net carbon along the planning horizon (ton C)
nCB: negative deviation for the carbon balance criterion (ton C)
Volume: Total volume along the planning horizon (m^3)

Table 4
Results of the GP models (best-compromise or satisficing schedules)
(Resultados dos modelos de programação por metas (melhor compromisso ou satisfação de programas))

	w1=w2=w3=1		***w2=w3=1; w1=2***		***w1=w3=1; w2=2;***		***w1=w2=1; w3=2;***	
	weighted	**minmax**	**weighted**	**minmax**	**weighted**	**minmax**	**weighted**	**minmax**
NPV (*10^6 €)	31,11	28,93	31,20	31,57	31,05	28,85	31,00	25,99
niH+piH (m3)	55.308	646.476	67.151	696.153	50.066	327.573	107.417	1.147.643
nif+pif (ha)	0	0	0	0	0	0	0	0
nkl+pkl (m3)	0	0	0	0	0	0	0	0
Carbon Balance (Tm)	61.700	69.146	61.682	64.842	61.625	68.712	64.180	70.157
Volume (m^3)	1.046.223	1.033.637	1.046.258	1.042.516	1.046.305	1.035.385	1.050.647	1.010.222
Average rotation	110	110	108	107	108	111	108	116

w1: value of the preferential weight assigned to the first propority level
w2: value of the preferential weight assigned to the second propority level
w3: value of the preferential weight assigned to the third propority level
weighted: Lexicographic weighted goal programming model
minmax: Lexicographic minmax goal programming model

It is important to note that while the differences in terms of carbon captured are important, however the differences in terms of NPV, total volume or average rotation are not significant. In short, it seems that some of the goals usually introduced in forest management are inelastic to changes in the value of the weights or even to the type of method used. Finally, it should be noted that the solutions presented are robust to changes in the values of the preferential weights as it is shown in Table 4.

DISCUSSION

The methodologies used in this paper show a great potentiality in forest management when the classic scope is increased with the consideration of additional goals like the capture of carbon. This conclusion is valid for a plantation case as well as for an established stand.

Let us now compare the results obtained in the two cases studied. Thus, the carbon captured does not depend of the specie used, if the temporal horizon is large. As Harmon (2001) states, the scale considered has a strong influence when the carbon captured by different stands is compared. Nevertheless, due to the different timber densities gross carbon is slightly larger for *Pinus radiata*. That is, the poplar although has a shorter cycle with respect to the pine, presents a lower carbon balance because of the density of both type of woods (0.30 kg/m^3 for poplar and 0.385 kg/m^3 for pine). This fact should be taken into account in order to choose the right specie when the maximisation of the capture of carbon is a primary goal.

When the planning horizon is larger than 100 years the net carbon in both species is rather constant, although slightly superior in the case of the poplar. This result is due to the fact that the number of consecutive harvests for the pine is not still enough to achieve a balance with respect to the carbon.

On the other hand, thinning operations imply an increase in the net carbon since they are essential in order to obtain logs with a longer life final use. However, this fact is compensated for the larger amount of carbon emitted in the short run. Thus, in order to maximise the carbon captured by this type of plantations thinning operations should be avoided (Bateman and Lovett, 2000). However, it is rather obvious that this type of policy is not viable from a private point of view. In fact, this type of policy would lead to an increase in the figure of gross carbon as well as an enlargement of the rotation age but with a very bad economic performance.

In the last sections it has been proved that the European subsidies for afforestation programs as well as the implementation of subsidies per ton of carbon captured are not efficient policies in order to approximate the private and the environmental optima. A possible solution for this problem will consist in establishing more specific aids by supplementing, for example, the timber price. That is, to encourage the enlargement of the rotation age by subsidising the timber price. Without entering in a deep discussion about how to implement this policy, the two cases studied clearly show how due to the proximity between both optima the necessary amount of money to support this type of policy will not be too large. Thus, in the case of afforestation with *Pinus radiata* and in a context with subsidies it would be necessary a price subsidy around 3 €/m^3.

Alternatively, it is interesting to note that most profitable plantations (e.g., poplar) present an environmental optimum slightly inelastic to increases in the figure of subsidies. Despite the proximity between both optima in the cases analysed, if the rotation age increases, the divergence between them also increases. Thus, in Romero et al. (1998) can be verified how in an afforestation case with *Fagus sylvatica* considering the carbon captured the rotation age corresponding to the private optimum is around 50 years, while the environmental optimum is achieved at 150 years.

In the case of permanent stands when the carbon captured is considered, the management guidelines are very different with respect the traditional ones. Thus, traditionally the primary objective in forest management has consisted in the maximisation of the timber volume looking for an even-flow policy and a regulated forest (i.e., the hypothesis of "normal forest"). However, the results shown in the pay-off matrix clearly show how the maximisation of the carbon captured is incompatible with these traditional objectives.

Finally, is important to note that the two Lexicographic Goal Programming models provide similar solutions, which represent attractive lines of action from a managerial point of view.

CONCLUSIONS

The Goal Programming models used in this paper have revealed as a powerful approach to integrate the carbon captured in conjunction with other criteria in forest management problems.

It is important to note that if we account only the carbon stored in the logs, there is a great disparity between gross and net carbon. Moreover, the amount of carbon captured is strongly influenced by factors like the timber density, the silvicultural systems, or the planning horizon chosen. In the two cases studied in terms of rotation age, NPV and even gross carbon there are not significant differences for the private and environmental optima. However, if we account the net carbon the differences are relevant for the two species.

The current European subsidies as well as the introduction of a subsidy per ton of carbon captured does not guarantee a larger gross or net capture. The only effect of this type of policy is to increase the profitability of the forest owner. These results seem to suggest the necessity to design different public policies in order to internalise this type of positive externality.

Moreover, it has been demonstrated how the maximisation of the carbon captured clearly conflicts with the traditional objectives that lead to the idea of "normal forest". Even though, this important result derives from a single case, it seems interesting because open the doors to the use of the modern techniques of optimisation in forest management.

Finally, the models introduced provide solutions that can be implemented by the forest manager. Thus, the best-compromise or satisficing solutions generated by the lexicographic GP models seem attractive. This is especially true when the solutions shown in Table 4 are compared with the single optimisation solutions contained in the pay-off matrix shown in Table 3. For instance, if we compare the solution that maximises the net present value (column 1 of Table 3) with the lexicographic weighted GP solution for equal weights (column 1 of Table 4), the latter solution present important advantages in terms of the three forestry goals considered. Thus, the opportunity costs for these improvements entail a reduction of around 11% of net present value and an increase of around 24% in the total carbon balance. Moreover, the timber volume harvested and forest rotation ages for the eight solutions obtained are rather similar. In short, solutions presented in Table 4 seem quite acceptable from a managerial point of view.

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REFERENCES

BATEMAN, I.J.; LOVETT, A.A. Estimating and valuing the carbon sequestered in softwood and hardwood trees, timber products and forest soils in Wales. **Journal of environmental management**, v.60, p.301-323, 2000.

DÍAZ-BALTEIRO, L.; ROMERO, C. Forest management optimisation models when carbon captured is considered: a goal programming approach. **Forest ecology and management**, v.174, p.447-457, 2003.

DÍAZ-BALTEIRO, L.; ROMERO, C. Rentabilidad económica de especies arbóreas de crecimiento medio y lento: algunas reflexiones de política forestal. **Revista española de economía agraria**, v.171, p.85-108, 1995.

FAUSTMANN, M. Berechung des wertes welchen waldboden sowie noch nicht haubare holzbestände für die waldwirtschaft besitzen. **Allgemeine forst und jagd zeitung**, n.15, 1849. (Also included in: FAUSTMANN, M. Calculation of the value which forest land and immature stands possess for forestry. **Journal of forest economics**, v.1, p.7-44, 1995.

HARMON, M.E. Carbon sequestration in forests: addressing the scale question. **Journal of forestry**, v.99, n.4, p.24-29, 2001.

HARTMAN, R. The harvesting decision when a standing forest has value. **Economic inquiry**, v.16, p.52-58,1976.

HERRUZO, A.C. La forestación de tierras agrarias y el desarrollo rural en la unión europea: una visión desde España. **Série técnica IPEF**, n.34, p.121-138, 2001.

HOEN, H.F. The Faustmann rotation in the presence of a positive CO_2-price. In: LINDAHL, M.; HELLES, F., ed. **Proceedings of the Biennial Meeting of the Scandinavian Society of Forest Economics**. Gilleleje, 1994. p.278-287.

HOEN, H.F.; SOLBERG, B. Potential and economic efficiency of carbon sequestration in forest biomass through silvicultural management. **Forest science**, v.40, p.429-451, 1994.

IGNIZIO, J.P.; CAVALIER, I. **Linear programming**. New Jersey: Prentice Hall,1994.

MUTKE REGNERI, S.; DÍAZ BALTEIRO, L.; GORDO ALONSO, J. Análisis comparativo de la rentabilidad comercial privada de plantaciones de *Pinus pinea* L. en tierras agrarias de la provincia de Valladolid. **Investigaciones agrarias: serie recursos y sistemas forestales**, v.9, n.2, p.270-303, 2000.

NABUURS, G.J.; MOHREN, F.; DOLMAN, H. Monitoring and reporting carbon stocks and fluxes in Dutch forests. **Biotechnol. Agron. Soc. Environ.**, v.4, p.308-310, 2000.

RODRÍGUEZ, L.C.E.; BUENO, A.R.B; RODRÍGUEZ, F. Rotaçôes de eucaliptos mais longas: análise volumétrica e econômica. **Scientia forestalis**, v.51, p.15-28, 1997.

ROMERO, C. **Handbook of critical issues in goal programming**. Oxford: Pergamon Press,1991.

ROMERO, C.; RÍOS, V.; DÍAZ-BALTEIRO, L. Optimal forest rotation age when carbon captured is considered: theory and applications. **Journal of the operational research society**, v.49, p.121-131, 1998.

ROW, C.; PHELPS, R.B. Wood carbon flows and storage after timber harvest. In: SAMPSON, R.N.; HAIR, D., ed. **Forests and global change**. Washington: American Forests Society, 1996. v.2, p.27-58.

VAN KOOTEN, G.C.; BINKLEY, C.S.; DELCOURT, G. Effect of carbon taxes and subsidies on optimal forest rotation age and supply of carbon services. **American journal of agricultural economics**, v.77, p.365-374, 1995.