FOREST MANAGEMENT AND CARBON CAPTURED: ANALYTICAL ASPECTS AND POLICY IMPLICATIONS

L. Díaz Balteiro [1], C. Romero [2]

[1] High Technical School of Agricultural Engineering. Avda. Madrid, 57, 34071 Palencia. Spain
[2] High Technical School of Forestry Engineering. Ciudad Universitaria s/n, 28040 Madrid. Spain
balteiro@iaf.uva.es

SUMMARY

In the last few years there has been an increasing tendency to consider forest ecosystems as possible sinks of carbon dioxide. In this way, it is attempted to mitigate the dramatic increase of global emissions of this gas in the industrialised countries. This new context implies modifications in basic aspects of the forest management discipline, like the determination of the forest optimal forest rotation, including the new European grants. In this paper, some recent experiences in this direction will be critically reviewed and some new ideas will be considered. With this purpose in mind three cases are studied: one species of short rotation *(Populus sp.)*, another one of medium rotation *(Pinus radiata* D. Don*.)* and finally one species of long rotation *(Pinus sylvestris* L.).

KEY WORDS: Carbon sinks
Forest management
Forest economics

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. That is, the forest ecological function as CO_2 sinks is totally considered in the protocol as a policy 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). Recently, in Bonn Climate Deal (July 2001) afforestation and reforestation projects are included among the acceptable actions for carbon sinks (VV.AA., 2001).

On the other hand, the agro-environmental policies within the Agenda 2000 condition the development of the common agriculture leading to a more sustainable agriculture. In this way, several social demands besides the private commodities are met. Within this policy framework we have the different types of aids and subsidies for encouraging forest investments in agriculture lands (Reg. 1257/99, Reg. 1750/1999) that they have been recently transferred to the Spanish legislation (Royal Decree 6/2001). This type of aids and subsidies are very important in order to encourage the forestry activities (ARD) gathered in the Kyoto Protocol. It is interesting to note that these new aids in comparison with the grants and subsidies implemented in the nineties do not encourage the «subsidies grow» and also they establish a minimum rotation age of 15 years for the short rotation species.

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, when we work 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).

The paper is organised as follows. First the methodology will be presented. After that, and with its help, the environmental and economic implications of considering the carbon captured for three types of afforestation will be analysed.

MATERIAL AND METHODS

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. By accepting the working hypothesis stated by Row and Phelps (1996) the calculation of the carbon captured, for each different timber use, was made. 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 environmental optimum.

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. 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:

$$NPV = \frac{I(t)\,e^{-it} - K - G - \sum_s Y_s\,e^{-is} + \sum_l C_l\,e^{-il}}{1 - e^{-it}} + K_1 + P_m \qquad P_c \qquad [1]$$

with:

$$\frac{e^{(-il)}\,(e^{(-it)} - 1)}{(e^{(-il)} - 1)}$$

$$\frac{e^{(-il)}\,(e^{(-i5)} - 1)}{(e^{(-il)} - 1)}$$

$$\frac{e^{(-il)}\,(e^{(-i20)} - 1)}{(e^{(-il)} - 1)}$$

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:

$$NPV \quad \frac{I(t)\ e^{i\,t}\ K\ G\quad {}_{s}Y_s\ e^{i\,s}\quad {}_{l}C_l\ e^{i\,l}\quad A\ {}_{r}C_a\ e^{ir}\quad A\ {}_{v}C_e\ e^{iv}}{1\ e^{i.t}} \quad K_1\quad P_m\quad P_c \qquad [2]$$

with:

$$\frac{e^{(\ i l)}\ (e^{(\ i t)}\ \ 1)}{(e^{(\ i l)}\ \ 1)}$$

$$\frac{e^{(\ i l)}\ (e^{(\ i 5)}\ \ 1)}{(e^{(\ i l)}\ \ 1)}$$

$$\frac{e^{(\ i l)}\ (e^{(\ i 20)}\ \ 1)}{(e^{(\ i l)}\ \ 1)}$$

Where C_a 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. 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).

Three species with very different rotation ages and different financial support systems were analysed. First, we will study poplar *(Populus sp.)*, that is a hardwood producer with short rotation ages (12-15 years), with excellent yields in many areas of Spain. Second, we will study radiata pine *(Pinus radiata* D. Don*.)*, that is abundant in the north of Spain and widely used for the afforestation of agriculture lands and with a rotation age of around 35 years. Finally, a long rotation age species (100 years) like Scots pine *(Pinus sylvestris* L.) has been considered. Table 1 shows the main technical and economical characteristics of the three species studied. More information about poplar and radiata pine can be seen in Díaz-Balteiro and Romero (2001a) and Díaz-Balteiro (2001), respectively. In order to represent the evolution of Scots pine the software «Silves 1.0» (Río, 1999, Río and Montero, 2001) was used. This simulator is especially appealing because of its versatility to combine dates coming from natural as well as regeneration stands.

Table 1

Main financial and technical aspects of the three afforestations considered

	Populus sp.	Pinus radiata	Pinus sylvestris
Afforestation cost	1,272 €/ha	1,563 €/ha	1,803 €/ha
Annual cost	30 €/ha year	12 €/ha year	24 €/ha year
Cultural operations costs *	1,190 €/ha	1,966 €/ha	1,194 €/ha
K_1	1,272 €/ha	1,266 €/ha	1,281 €/ha
P_m	150 €/ha	180 €/ha	181 €/ha
P_c	0 €/ha	166 €/ha	182 €/ha
Volume obtained at private optimum	356 m^3	377 m^3	237.9 m^3
Thinnings	no	yes	yes
Discount rate	7 %	7 %	4 %
Timber price at harvest time	60-68 €/m^3	51 €/m^3	71.4-97.4 €/m^3

RESULTS

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 18,423 €. 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 an infinite 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 t/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 2 shows the gross and the net carbon according to the afforestations considered. Table 3 shows the results obtained in terms of profitability.

As it was commented above, to circumvent the difference between the private and the environmental optimum a subsidy ranging between 20 and 200 € 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

Table 2

Gross and net carbon for the three species along diverse rotations and planning horizons. Technical rotation is shaded

		GROSS CARBON (t/ha)				NET CARBON (tm/ha)			
	ROTATION	**100 years**	**120 years**	**150 years**	**200 years**	**100 years**	**120 years**	**150 years**	**200 years**
Populus sp	**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	**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
Pinus sylvestris	**150**	*	185.37	252.51	370.74	*	157.27	150.45	172.10
	140	*	179.15	263.36	358.30	*	122.79	150.05	129.05
	130	*	170.48	270.03	389.55	*	107.48	147.35	148.88
	120	*	189.22	276.96	408.16	*	119.57	149.69	153.76
	110	*	200.75	280.82	419.33	*	125.60	152.12	158.02
	100	141.06	208.20	282.12	423.18	116.37	124.26	154.66	165.94
	90	128.65	212.85	257.29	413.18	83.70	124.28	105.80	130.54
	80	114.99	214.53	278.56	429.18	59.04	113.68	107.18	127.89
	70	126.79	199.08	283.29	398.17	62.80	79.31	106.98	81.39
	60	132.79	195.67	252.63	421.05	72.74	75.53	66.84	118.34

Table 3

Main financial results with different carbon prices

		NPV no grants	NPV + gross C	NPV + net C	Rot.	NPV with grants	NPV with grants + +gross C	NPV with grants + + net C	Rot.	Gross C	Net C
0 €/t	**Populus sp.**	16,968.4	16,968.4	16,968.4	14	18,242.5	18,242.5	18,242.5	15	39.7	49.2
	Pinus radiata	-881.2	-780.7	-780.7	30	2,964.8	2,964.8	2,964.8	30	105.0	68.4
	Pinus sylvestris	-1,275.1	-1,275.1	-1,275.1	60	3,220.8	3,220.8	3,220.8	60	84.2	70.4
25 €/t	**Populus sp.**	16,968.4	17,640.8	17,296.4	14	18,242.5	19,086.0	18,758.0	15	39.7	49.2
	Pinus radiata	-881.2	-629.9	-688.6	30	2,964.8	3,079.1	3,020.3	30	105.0	68.4
	Pinus sylvestris	-1,275.1	-1,165.9	-974.2	60	3,220.8	3,330.0	3,261.8	60	84.2	70.4
50 €/t	**Populus sp.**	16,968.4	18,313.3	17,624.4	14	18,242.5	19,748.6	19,092.7	15	39.7	49.2
	Pinus radiata	-881.2	-378.6	-496.0	30	2,964.8	3,330.4	3,213.0	30	105.0	68.4
	Pinus sylvestris	-1,275.1	-1,056.7	-673.3	60	3,220.8	3,439.1	3,302.9	60	84.2	70.4
100 €/t	**Populus sp.**	16,968.4	19,658.2	18,280.5	14	18,242.5	21,073.9	19,762.2	15	39.7	49.2
	Pinus radiata	-881.2	124.1	-110.8	30	2,964.8	3,833.1	3,598.2	30	105.0	68.4
	Pinus sylvestris	-1,275.1	-838.4	-71.4	60	2,881.8	3,657.5	3,385.1	60	84.2	70.4
150 €/t	**Populus sp.**	16,968.4	21,003.1	18,936.6	14	18,242.5	22,399.2	20,431.6	15	39.7	49.2
	Pinus radiata	-881.2	626.8	274.4	30	2,964.8	4,335.7	3,983.4	30	105.0	68.4
	Pinus sylvestris	-1,275.1	-620.0	530.4	60	2,881.8	3,875.9	3,467.2	60	84.2	70.4
200 €/t	**Populus sp.**	16,968.4	22,348.0	19,592.6	14	18,242.5	23,724.5	21,101.0	15	39.7	49.2
	Pinus radiata	-881.2	1,129.4	659.7	30	2,964.8	4,838.4	4,368.6	30	105.0	68.4
	Pinus sylvestris	-1,275.1	-401.6	1,132.3	60	2,881.8	4,235.0	3,569.5	55	66.4	76.5

Rot. = Rotation.
Discount rate is 4 % for *Pinus sylvestris* L. and 7 % for the other two species.

profitability. In fact, the NPV increase in a 27 % if the gross carbon is considered with a subsidy of 200 €/t C.

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) coincide 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 3). 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 t C/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 t C /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, then the rotation age does not change. The increase in the subsidy once a certain threshold is surpassed can make the investment profitable just by considering only the gross carbon and without the European financial aids. Thus, a subsidy of 100 €/t C implies that the NPV referred to the gross carbon reaches the figure of 24.1 €/ha. It is interesting to note that these results are robust to changes in the discount rate.

Regarding Scots pine the corresponding environmental optimum is around 80 years. For this rotation age the gross carbon captured achieves a figure of 115 t C/ha. Without subsidies, this type of plantation is not financially viable within the set of assumptions considered, since the NPV for this age is of –1,504 €/ha. For this scenario the rotation age of the private optimum is 60 years with a NPV of –1,275 €/ha. The gross carbon captured for this age slightly surpasses the 84 ton C/ha as can be seen in Table 3. That is, to give up to a 15 % of NPV would improve the gross carbon captured in around 37 %. In terms of net carbon the opportunity cost between the private and the environmental optimum is of 22.5 t, that is, near a 32 % of the net carbon in the private optimum.

As it happened in the preceding case, the existence of subsidies do not alter the optimum rotation age, but provokes an important increase in the profitability of the investment, surpassing the figure of 3,220 €/ha (around of 26 % of this NPV is due to the thinning regime). These results are highly inelastic to the introduction of a subsidy per ton of carbon captured (see Table 3). In fact, only when the subsidy achieves the figure of 200 €/t of carbon captured, the rotation age changes. Even for this extreme case the profitability of the investment increases a 31 % if the subsidy is granted considering the gross carbon. In short, the introduction of this type of policy does not approximate the private and the environmental optima. This conclusion keeps its value if the C captured is measured in gross or net terms. Independently of measuring the carbon captured in gross or net terms. The implementation of a sensitive analysis shows how in these cases there is a bigger elasticity with respect to changes in the value of the discount rate. Thus, small reductions in the discount rate (up to a 3 %) increase the rotation age of the private optimum up to 75 years that is a figure very near with respect to the one corresponding to the environmental optimum.

DISCUSSION

It is important to note the evolution of the gross and the net carbon captured along the time. Thus, Figure 1 shows how while the gross carbon grows in every rotation or plantation cycle, the accumulated net carbon diminishes at an increasing rate from the second plantation cycle onwards. However, it is easy to check how the net carbon in each plantation cycle starts to decrease up to achieve an equilibrium between the fourth and the fifth plantation cycle. This «steady state» represents a limit for the efficiency of the afforestation programs as suitable policy to mitigate the problem.

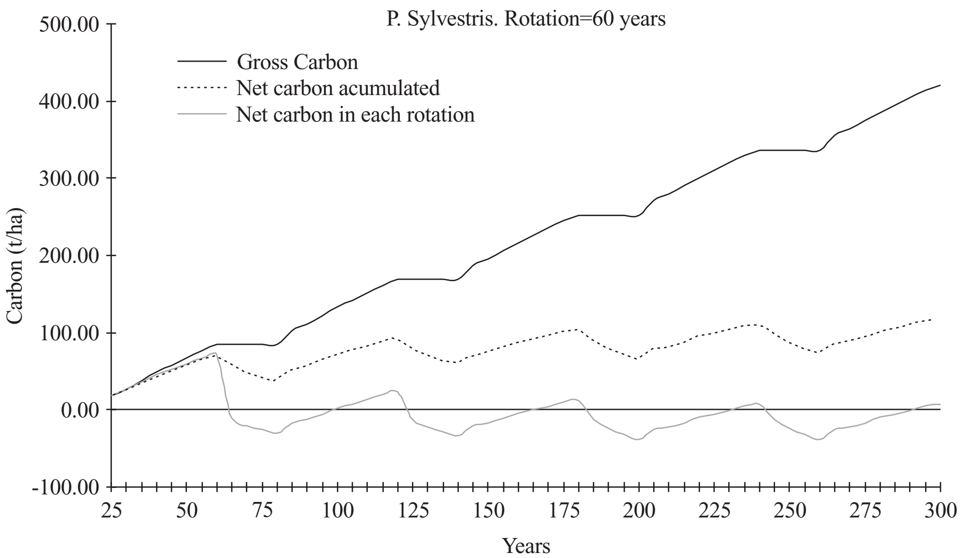

Fig. 1.–Differences between several measures of the carbon captured along the planning horizon

Let us now compare the results obtained in the three cases studied. Thus, the gross carbon captured does not depend of the species used, if the planning horizon is large and the corresponding rotation age is relatively small. Nevertheless, due to the different timber densities gross carbon is slightly larger for Pinus radiata. That is, poplar plantations although have a shorter cycle with respect to the pine, present 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 species when the maximisation of the capture of carbon is a primary goal.

If we compare the results obtained for the three species considered the Scots pine is the species with a lower carbon captured. Thus, for a planning horizon of 100 years, the gross carbon captured for *Pinus sylvestris* L. is less than the half that the carbon captured by Populus sp. or *Pinus radiata* D. Don. for a maximum sustainable yield rotation age. However, when the net carbon is measured the values obtained show an opposite trend. In fact, although for poplar and radiata pine the carbon captured is very similar, for Scots pine the figure of carbon captured is bigger. It is important to note the planning horizons considered do not cover the minimum number of cycle plantations required in order to achieve an equilibrium with respect to the net carbon.

These results reinforce the differences previously established between the two procedures considered for measuring the carbon captured by the timber stands. In this sense, this type of information can help to answer a question usually raised by forest managers when a new objective is introduced in the management process: Is it more suitable to afforest with short rotation or with long rotation species? The answer to this question depends upon the carbon considered, what is closely related with the social perception towards this type of problem. Thus, if society considers that in a relatively short period of time (i.e., some few decades) the atmosphere warming provoked for the CO_2 emissions will not be a real problem then the best option are short rotation species. On the contrary, if it is considered that this problem is a long term problem, then the right reference will be the net carbon, and consequently long rotation species should be the most suitable. Therefore, as Harmon states (2001), the scale considered has a strong influence when the carbon captured by different stands is compared.

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. Thus, these type of subsidies are important just because they increase the profitability of the underlying investments. However, its efficiency in order to approximate the private and the environmental optima is very small and completely disappears for the Scots pine case. Figure 2 shows the importance of these type of subsidies for each one of the species considered. It was also checked how the importance of the maximum subsidy for the carbon captured (gross and net) of 200 €/t C, decreases when the rotation age increases. With the exception of Pinus radiata, the revenues derived from timber or from the European subsidies are more important that the revenues derived from an hypothetical subsidy to the carbon captured.

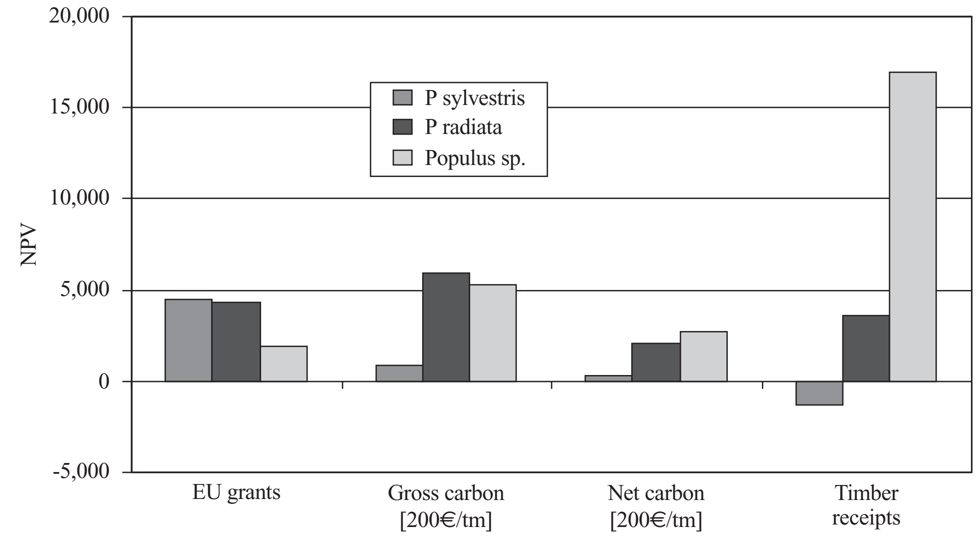

Fig. 2.–Importance of the different revenues for each afforestation, and considering a carbon price of 200 €/t C.

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 softwood 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 €/$m^{3.}$ Another possible policy will consist in introducing an annual subsidy (without any relation with the rotation age) in order to approximate both optima. Huang and Kronrad (2001) develop this alternative for *Pinus taeda* L. plantations. By using a similar procedure for the Scots pine, the annual subsidy in order to equate the private optimum (rotation of 60 years) with the environmental optimum (rotation of 80 years) would be equal to 27 €/ha year when no European subsidies are considered. This annual subsidy reduces to 16 €/ha year when these type of subsidies are taken into account. It is important to note that these figures are clearly smaller than the current maintenance and compensatory premiums. However, the implementation of this new scheme seems much more complicated.

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, as it happens with *Pinus sylvestris* L. Thus, in Romero *et al.* (1998) can be verified how in another afforestation case with *Fagus sylvatica* L. 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.

Finally, it is important to note that in this paper we have not considered the carbon captured in permanent stands. To undertake this type of task it seems useful to resort to multi-criteria methodologies that allow an integration of the carbon captured objective with the objectives used traditionally in forest management. In Díaz-Balteiro and Romero (20001b) can be found a Goal Programming formulation of this type of problem for a *Pinus sylvestris* L. forest.

CONCLUSIONS

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. With the exception of the short rotation species 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 long rotation species studied *(Pinus radiata* D. Don and *Pinus sylvestris L.)*.

The current European subsidies as well ass the introduction of a subsidy per ton of carbon captured does not guarantee a larger gross or net carbon capture. The only effect of this type of policy is to increase the private 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.

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RESUMEN

Gestión del bosque y captura de carbono: aspectos analíticos e implicaciones políticas

En los últimos años ha habido una tendencia creciente de considerar a los ecosistemas forestales como posibles sumideros de dióxido de carbono. En este sentido, se intenta mitigar el importante incremento de las emisiones de este gas en los países industrializados. Este nuevo contexto implica modificaciones en aspectos básicos de la gestión forestal, como la determinación del período óptimo de rotación, incluyendo las nuevas subvenciones europeas. En este artículo se hace una revisión crítica de algunas experiencias recientes, y se consideran nuevas ideas. Con este propósito se estudian tres casos: una especie con período de rotación corto *(Populus sp.)*, otra especie con un período de rotación medio *(Pinus radiata* D. Don.), y finalmente una especie con un período de rotación largo *(Pinus sylvestris* L.).

PALABRAS CLAVE: Sumideros de carbono
Gestión forestal
Economía forestal

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