Decision Support for Multiple Purpose Forestry, April 23-25, 2003, Vienna – Austria

INCLUDING CO_2-FIXATION IN THE EVALUATION OF SILVICULTURAL ALTERNATIVES IN SCOTS PINE STANDS IN SPAIN

Gregorio Montero[1], Miren del Río[1*], Isabel Cañellas[1], Alberto Rojo[2] and Marta Muñoz[1]

[1]Centre for Forest Research. CIFOR – INIA
Ctra. A Coruña km 7, 28040 Madrid (Spain)
delrio@inia.es

[2]Departamento de Enxeñería Agroforestal. Universidade de Santiago de Compostela

Keywords: silvicultural alternatives, biomass**,** CO_2 fixation, modelling, Scots pine

Summary: *In this work the biomass and carbon storage for Pinus sylvestris L. stands in central Spain with two silvicultures have been estimated and compared. 316 trees were felled and weighted by different components and allometric equations have been adjusted to relate tree biomass components to diameter. Found below/aboveground biomass ratio per tree is around 0.25. Using yield tables the stand biomass per hectare has been compared between extensive and intensive silvicultures, varying the rotations and thinning regimes. The biomass production of total crop at rotation age is 967 t/ha for the extensive silviculture (140 years) and 911 t/ha for the intensive silviculture (100 years), which involve rates of carbon storage per year of 3.5 and 4.6 t/ha·year respectively. The intensive silviculture produces more stem biomass per year and bigger trees, which allow wood products with longer lifetime, resulting in a higher efficiency in the* CO_2 *fixation.*

1. Introduction

A global climate change has been produced by the increment of the greenhouse gases in atmosphere. 75% of gases with greenhouse effect belongs to carbon dioxide (CO_2). The forest, through the photosynthesis process, can fix an important amount of CO_2, participating in the mitigation of the global climatic change. The forests cover more than 25% of the emerged surface of the world ($4.1*10^9$ ha) and it is estimated that 80% of carbon of the aboveground biomass and 40% of root and vegetal residues carbon is included in the forest ecosystems approximately (Dixon *et al.*, 1994).

The Kyoto Protocol proposes the increment of the CO_2 fixation as an objective of the criteria of sustainable management of forest. In this sense the forest science should apply new silvicultural methods to optimise the carbon fixation. The denominated *carbon silviculture* is based in the longer rotation period to obtain products with higher quality and longer lifetime and in the intensification of silvicultural treatment to permit more forest biomass extraction. In the same way, harvesting methods which increase the biomass fractions extracted from the forest could improve the CO_2 fixation. However the efficiency in the CO_2 fixation by forest should be reached by a proper combination between silvicultural treatments and harvesting methods.

To value the efficacy of each harvesting method it is necessary to know and quantify the different biomass fractions of each felled tree. The typical accepted fractions are: stem, branches bigger than 7 cm of diameter, branches with a diameter between 2 and 7 cm, branches with less than 2 cm of diameter and root and stump biomass. Depending on the biomass components which are extracted out the forest with harvest or are left on soils to their decomposition and soil incorporation we will have a more or less efficient management in relation to the CO_2 fixation. The silviculture and the harvesting system could manipulate the mean life of products. The time which the carbon is in the tree or in diverse forest

products, that the society use, is considered as a carbon storage, although an important part of it is out the forest ecosystem.
Capture-emission process of CO_2 by forest is a complex system that we need to know with precision to develop a proper management. The simplification of main CO_2 reservoirs (Ordoñez and Masera, 2001) reduces the system to four groups: aboveground biomass, belowground biomass, detritus materials on soils and forest products used by society. Each of these stocks have a different lifetime and different routes in their incorporation into atmospheric CO_2 and all of them make more difficult their management through the silviculture.

In Spain, Scots pine is the most important conifer tree species in mountain regions and its area covers 1,280,000 ha (19% of the total forest area). Since the beginning of the nineteenth century, general forestry management objectives have not varied much, though particular features of the major objectives have been reformulated to adjust to changing social and environmental circumstances. The objectives pursued in the management of *Pinus sylvestris* are to guarantee the survival, stability and diversity of the species and to obtain high quality wood production. But now we have to include in these management multi-use objectives (the optimisation of the different possible land uses, including non-commercial indirect benefit) and the sustainability concepts, like CO_2 fixation.

Available tools for simulating silvicultural alternatives in Scots pine stands in Spain do not offer required information to guarantee sustainable management. Several stand and size class growth models have been developed in the last decade for even-aged stands (Rojo and Montero, 1996; Río and Montero, 2001; Bravo and Montero, 2003) and nowadays tree level models are being built (Palahi, Pukkala, Miina and Montero, 2003). These models allow the simulation of different silvicultures and to knowledge of the structure and the timber production of stands. However some fundamental aspects like sequestering carbon are not considered.

The aim of this study is to estimate the biomass and carbon in *Pinus sylvestris* L. stands in central Spain and to evaluate the CO_2 fixation with different silvicultures in order to help in decision-making concerning these management alternatives. Comparison between two silvicultural regimes, one moderate and other more intensive, is presented. The biomass production in relation to their efficiency in the CO_2 fixation will be analysed for each silvicultural treatment.

2. Material and Methods

2.1. Study area

Scots pine woods in the Central mountain range of Spain are situated from 1200 to over 2000 m. The phytoclimatic types are mainly oro-borealoid, but also subnemoral where stands of highest quality develop. The Central mountain range is a siliceous area where soils are rather deep, fairly sandy-textured, permeable, with a moderate to highly acidic pH. Scots pine forms frequently pure and even-aged stands, but sometimes it appears in mixed stands with *Pinus pinaster* Ait. or *Quercus pyrenaica* Willd.

2.2. Data

In order to quantify the biomass of different parts of the tree, 316 pines were felled in three Scots pine forests of the Central mountain range of Spain. In selected forest the standard silvilculture of Scots pine in this area has been applied. The sample trees were distributed into diameter classes ranging from 5 to 75 cm. Thickest diameter classes were represented with at least three trees. Felled trees were cut up and separated into the following components: stem; branches with a diameter over 7 cm; branches with diameter between 2 and 7 cm; and branches thinner than 2 cm including needless.

Branches components were weighted in the forest and, afterwards, the dry weights were calculated in the laboratory through a sample of each fraction dried to constant weight. In the same way, the percentage of needless and its fresh/dry weight factor were estimated in a sample of the thinnest branches component.

Due to the difficulty and cost of root system measure only one tree per diameter class was chosen to extract and weight the root system biomass. In field the root systems were weighted in three parts, stump

root, roots with diameter over 7 cm and thinner roots; but the sum of them was used for developing the total root system equation.
Stem wood biomass was calculated through wood volume applying the density coefficient of Scots pine wood in the study area, 0.418 kg/m^3 (Gutierrez, Baonza and Fernández-Golfín, 1997). Estimates of stem volume provided in the applied yield model were used.

2.3. Allometric equations

Allometric equations were developed for each component to relate their dry weight to the diameter at breast height of the tree. Different models were tested, selecting the best model for each component based on statistical criteria and the distribution of residuals. The tested models are:

$$Y = a_o + a_1 \cdot d + a_2 \cdot d^2 \qquad (1)$$

$$Y = a_0 \cdot d^{a_1} \qquad (2)$$

$$Y = a_0 \cdot e^{a_1 \cdot d} \qquad (3)$$

where Y is biomass of the tree components in kg and d the diameter at breast height of the tree in cm.

2.4. Yield model

The estimation of biomass along the stand development was based on yield tables for Scots pine in Central mountain range of Spain available for two silvicultural models: light and heavy thinning regimes (Rojo and Montero, 1996). These yield tables were built using 104 plots situated in even-aged full-stocked stands of different ages and site qualities. The model includes 5 fundamental equations to estimate main stand variables (top and mean height, density, quadratic mean diameter and volume). The stand density evolution and the removed stand for the two thinning regimes were based on results of thinning experiments in the area (Madrigal, Gómez and Montero, 1985; Montero, Río and Ortega, 2000). Recently, diameter distributions calculated by the weibull function has been added to the model for the main stand before thinning.

Different component biomass per hectare for main stand before thinning, removed stand and total crop were estimated applying component biomass equations to yield tables. Diameter distributions were only available for the main stand before thinning so the biomass of a tree with the mean basal area were calculated and multiplied by the number of trees per hectare. The error associated with the used of the quadratic mean diameter instead of diameter distributions is around 5-10%, decreasing with stand age.

2.5. Silvicultural scenarios

Using the biomass equations and yield tables, the biomass and carbon balance of a Scots pine stand with two silvicultures have been simulated. The simulations have been made in high quality site because of the greater discussion about the vocation of Scots pine stands in the best sites. The site index is 26 m of top height at the reference age of 100 years. The two silvicultural scenarios are:

a) Model C - Extensive silviculture: medium densities, moderate low thinning and a rotation period of 140 years.
b) Model E - Intensive silviculture to achieve quality wood: low densities, heavy thinning with selection of best trees and a rotation period of 100 years.

The CO_2 fixed per biomass unit was calculated taking into account the biomass/carbon ratio (0.5) proposed by Kollmann (1959).

3. Results and discussion

3.1. Tree biomass

The selected models for all aboveground and belowground components of trees are given in Table 1. Adjusted models present R^2 over 0.8 and all parameters are statically significant, showing the equation for large branches (diameter > 7 cm) the poorest results. Only dicker trees have large branches, so this equation should not be used in trees with diameter smaller than 30 cm.

Table 1: Regression results of selected models for each biomass component of trees.

Biomass component	Equation	Parameter			R^2
		a_0	a_1	a_2	
Branches > 7 cm	$Y = a_0 \cdot e^{a_1 \cdot d}$	0.1506	0.1076	-	0.8020
Branches 2-7 cm	$Y = a_o + a_1 \cdot d + a_2 \cdot d^2$	-4.2214	0.2988	0.0291	0.8812
Branches < 2 cm	$Y = a_o + a_1 \cdot d + a_2 \cdot d^2$	1.2486	0.2166	0.0161	0.8569
Needles	$Y = a_o + a_1 \cdot d + a_2 \cdot d^2$	0.9419	0.1634	0.0121	0.8569
Root system	$Y = a_0 \cdot d^{a_1}$	0.0105	2.6268	-	0.9721

Biomass distribution in trees is influenced by their competitive status (Mákelá and Vanninen, 1998; Mátyás and Vargas, 2000), so developed functions should only be applied in stands treated with the standard silviculture of the area. For Scots pine in Scandinavia, Nilsson and Albrektson (1993) reported larger allocation to stems in high density stands. Because of this variation Claesson, Sahlén and Lundmark (2001) included also height and a measure of crown length as independent variables in biomass allometric functions for young stands.

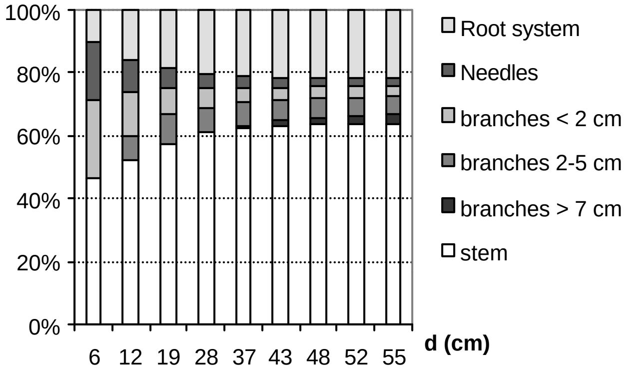

Figure 1: Variation of the percentages of biomass components per tree with diameter of tree

In figure 1 the variations of the distribution of biomass components per tree with the diameter a breast height are presented. The percentage of root system biomass per tree increases with the size of tree, maintaining near to 20% up to tree diameter of 30 cm. This percentage implies a belowground/ aboveground ratio around 0.25, which is in according to data given in Pardé (1980). Crown biomass percentage varies from 35-40% in young trees (diameter < 15 cm) to around 15% in largest trees. Total tree biomass varies from 12 kg for a diameter of 5 cm to 1800 kg for a diameter of 55 cm.

3.2. Stand biomass

The evolution of the total stand biomass (sum of all components biomass per hectare) with the two silvicultural models is presented in figure 2 for the main crop before thinning, removed crop, total or accumulated removed crop and total crop. The total biomass produced at age of 100 years is a little higher with the intensive silviculture than with the extensive one, with the greatest differences in the accumulate removed biomass. The biomass production of total crop at the end of the rotation is 967 t/ha for extensive silviculture (140 years) and 911 t/ha for the intensive silviculture (100 years).

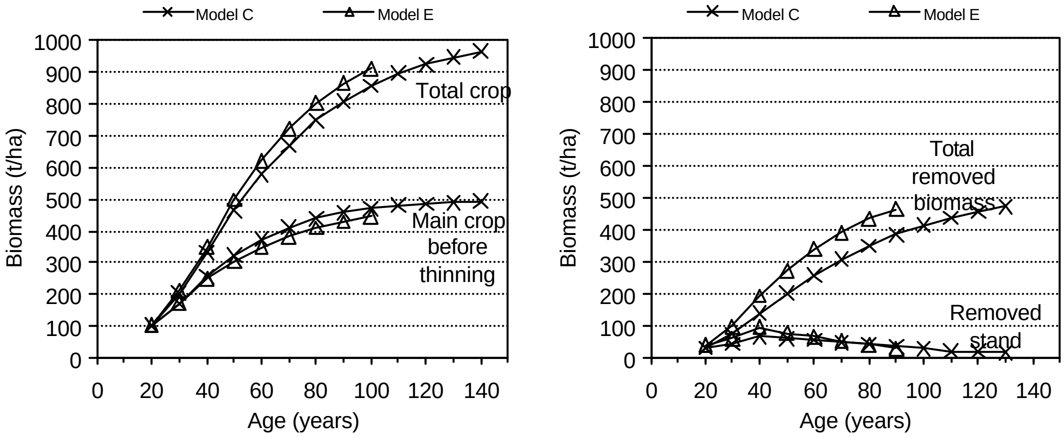

Figure 2: Evolution of total biomass with age for the two silvicultural models: C- Extensive, E- Intensive

The main stand development shows logically more biomass in the model C (extensive) than in the model E (intensive), with a difference of 26 t/ha at the age of 100 years (Figure 2). The biomass accumulated in the stand of model C at the end of the rotation (140 years) reaches nearly 500 t/ha.

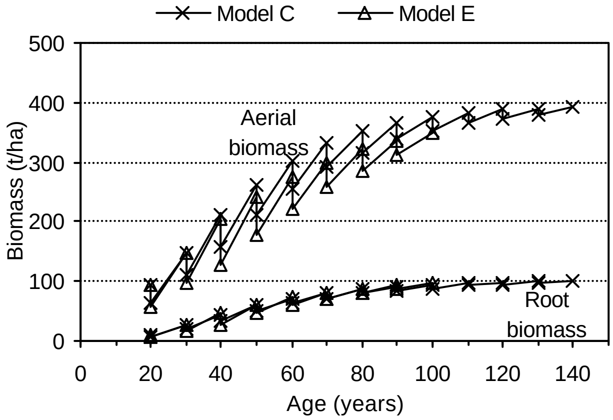

Figure 3: Evolution of aerial and root biomass with age in the main crop for the two silvicultural models: C- Extensive, E- Intensive

The evolution of aboveground-belowground distribution in main stand biomass for the two silviculture is presented in figure 3. It can be seen in this figure that for the aerial biomass there are considerable differences between both silvicultural models, but root system biomass are almost similar. The belowground/aboveground biomass ratio decreases with age maintaining up to the 60 years around 0.25 and 0.27 in model C and E respectively.

In order to compare more exactly the effect of the silviculture in carbon sequestration, the possible differences between both silvicultural models in the biomass distribution per tree should be studied. Allometric equations can be influenced by silviculture (Claesson, Sahlén and Lundmark, 2001), however, very small differences between thinned and non-thinned stands in allocation to aboveground biomass components were found in a Scots pine thinning experiment in Sweden (Valinger, 1993).

3.3. Removed biomass

A comparison between the total removed biomass components in the two models, including thinning biomass removed and the last harvest at the rotation age, allows us to identify the main differences in the stem biomass (Figure 4). The stems biomass involves the 60% of the removed biomass, so after the harvesting the 40% of the total biomass is being left in the forest if large branches are no used as firewood.

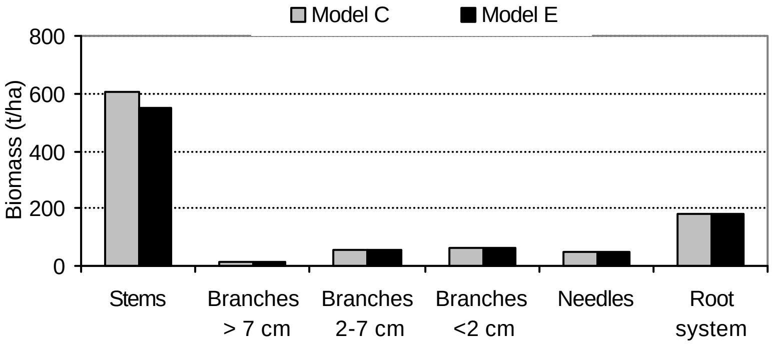

Figure 4: Distribution of biomass components of the total removed biomass (thinning and final harvest) for the two silvicultural models: C- Extensive, E - Intensive

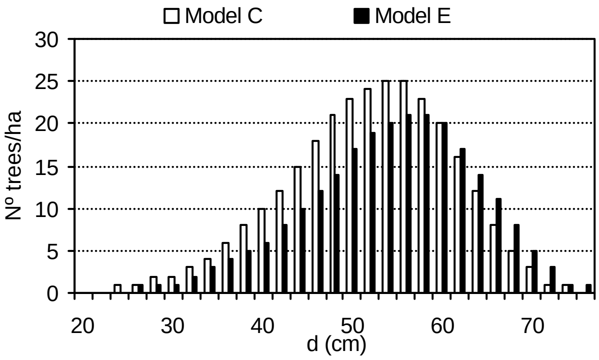

Figure 5: Diameter distribution at the end of rotation for the two silvicultural models: C- Extensive (rotation=140 years), E- Intensive (Rotation=100 years)

From silviculture point of view is more interested the carbon fixed by stem biomass, because we could modify it with different silvicultural techniques, changed the type of products and besides increment their mean life. For instance, short rotation periods will produce a higher mill wood percentage and longer rotation periods higher saw wood percentage that could use in house building, furniture, etc. with a longer mean lifetime. In the same way, an intensive silviculture permits to obtain bigger sizes and higher qualities of products than extensive silviculture with the same rotation period. In the simulated silvicultural models the diameter distributions obtained at the end of rotation with the intensive silviculture presents larger trees than with the extensive silviculture in spite of its sorter rotation (Figure 5).

An approximation to the percentages of stem biomass of trees with diameter at breast height under 20 cm and over 20 cm removed in each thinning have been estimated using the diameter distribution of the main crop at each age (Table 2). As can be seen in the figure 5 the harvested trees at the end of rotation are all larger than 20 cm, size which produces basically sawnwood. With these percentages the total removed stem biomass of both sizes, including thinning and the last harvest, have been calculated (Table 3). Of the total removed stem biomass around a 85% belong to larger trees (dbh>20cm), with similar values for extensive and intensive silviculture.

Table 2: Percentages of stem biomass of trees with diameter smaller and larger than 20 cm removed at each age in the two silvicultural models: C - Extensive, E - Intensive

Model	Diameter	Stand age												
		20	30	40	50	60	70	80	90	100	110	120	130	140
C	<20 cm	100	100	99	56	14	4	1	0	0	0	0	0	0
	>20 cm	0	0	1	44	86	96	99	100	100	100	100	100	100
E	<20 cm	100	95	72	12	2	100	0	0	0				
	>20 cm	0	5	28	88	98	99	100	100	100				

3.4. Carbon storage

In table 3 the total biomass production at the end of the rotation (total removed biomass) and the corresponding carbon storage are shown for models C and D. These data are presented in three fractions: stems of diameter < 20 cm, stems of diameter > 20cm and the sum of the other fractions (branches, needles and roots). The total biomass and carbon storage are higher in the model C than in model E. If the rotation of the silvicultural model is considered, the annual rate of biomass production is higher in the model E than in the model C, that involves higher rates of carbon fixation in forest biomass per year (4.6 and 3.5 t/ha·year in models E and C).

Table 3: Total and annual biomass production and carbon storage in the two silvicultural models: C- Extensive, E – Intensive. Total biomass fractions: Stem< 20 – stem biomass of trees with diameter < 20 cm; Stem>20 – stem biomass of trees with diameter > 20 cm; Others – branches, needles and roots.

	Total biomass (t/ha)		Total C storage (t/ha)		Annual biomass increment (t/ha·year)		Annual C storage (t/ha·year)	
	Model C (140 years)	Model E (100 years)	Model C (140 years)	Model E (100 years)	Model C	Model E	Model C	Model E
Stem<20	93.6	84.4	46.8	42.2	0.7	0.8	0.3	0.4
Stem>20	514.5	462.2	257.3	231.1	3.7	4.6	1.8	2.3
Others	359.0	364.2	179.5	182.1	2.6	3.6	1.3	1.8
Total	967.1	910.7	483.5	455.4	6.9	9.1	3.5	4.6

From the 484 t/ha of carbon storage produced along the 140 years of rotation in the model C, 304 t/ha has been accumulated in stems, while in the model E these values are reduced to 455 t/ha and 273 t/ha. It means a ratio of total to stem biomass of 1.59 and 1.67 for models C and E. This ratio is conceptually similar to the ratio of total to merchantable forest biomass used by Johnson and Sharpe (1983) to estimate Carbon content in forest from information provided in forest inventories, but without the carbon stored in litter, soil organic matter and under vegetation. Nevertheless, the assessment of C sequestration that includes ground vegetation, litter and soil organic matter can give a more realistic and accurate description of the C sequestration potentials, dynamics and sensitivity (Karjalainen, 1996).

Assuming similar carbon flows out of the forest per year in both models for the different biomass fractions, differences in annual carbon storages between silvicultural alternatives can be compared. Model E produces more biomass per year in all fractions (Table 3). Taking into account that the carbon accumulated in stem products returns to the atmosphere later than other fractions and that products derived from large trees (diameters > 20 cm) have longer mean life than products derived from small trees (diameter <20 cm), it is obvious the advantages of model E against model C.

4. Conclusions

In conclusion, most of the carbon in forest ecosystem is contained in tree boles. In a intensive silviculture we could develop a more efficient forest management related to carbon sequestration. With these silvicultural treatments we could obtain bigger trees and more stem biomass per year. Besides the different wood products will have a longer lifetime and the carbon will be more time sequestrated. Moreover, an intensive silviculture presents the additional advantage that it is more economical profit although some ecological requirements are necessary to applied this intensive silviculture.

This preliminary study in a high quality stand of Scots pine in Central System Mountain in Spain should be also analysed in others ecological conditions and with different growth models, including also the carbon flows of ground vegetation, litter and soil organic matter.

5. References

Bravo, F. and Montero, G. (2003) “High grading effects on Scots pine volume and basal area in pure stands in northern Spain”, *Annals of Forest Science,* (in press).

Claesson, S., Sahlén, K. and Lundmark, T. (2001) “Functions for biomass estimation of young *Pinus silvestris*, *Picea abies* and *Betula* spp. from stands in Northern Sweden with high stand densities”, *Can. J. For. Res.*, 16, 138-146.

Dixon, R.K., Brown, S., Houghton R.A.,, Solomon, A.M., Trexler, M.C. and Wisniewski, Y.J. (1993) “Carbon pools and flux of global forest ecosystems. *Science*, 263, 185-190.

Gutierrez, A., Baonza, M.V. and Fernández-Golfín, J. (1997) “Variaciones de la densidad de la madera de pino silvestre de los Sistemas Central e Ibérico”, Proceedings of the I Congreso Forestal hispano-luso, Pamplona, mesa 7, PA 229-234.

Johnson W. C. and Sharpe D.M. (1983) “The ration of total to merchantable forest biomass and its application to the global carbon budget”, *Can. J. For. Res*., 13(3), 372-383.

Karjalainen, T. (1996) “Dynamics and potentials of carbon sequestration in managed stands and wood products in Finland under changing climatic conditions”, *For. Ecol. Man.,* 80, 113-132.

Madrigal, A., Gómez, J.A. and Montero, G. (1985) “Estado actual de las investigaciones sobre claras. Primeros resultados obtenidos en una experiencia en masa artificial de *Pinus sylvestris* L. en el Sistema Central”, *Comunicaciones I.N.I.A. Serie: Recursos Naturales*, 42, 49 pp.

Mákelá, A. and Vanninen, P. (1998) “Impacts of size and competition on tree form and distribution of aboveground biomass in Sctos pine”, *Scan. J. For. Res.*, 16, 138-146.

Mátyás, C. and Vargas, G. (2000) “Effect of intra-specific competition on tree architecture and aboveground dry matter allocation in Scots pine”, *Investigación Agraria: Sistemas y Recursos Forestales,* fuera de serie nº1, 111-119.

Montero, G., Río, M. and Ortega, C. (2000) “Ensayo de claras en una masa natural de pino silvestre en el Sistema Central”, *Investigación Agraria: Sistemas y Recursos Forestales,* 1, 147-177.

Nilsson, U. and Albrektson, A. (1993) “Productivuty of needles and allocation of growth in young Scots pine trees of different competitive status”, *For. Ecol. Man.,* 62, 173-187.

Ordoñez, A. B. and Masera, O. (2001) “Almacenamiento de carbono en un bosque de *Pinus pseudostrobus* en Nuevo San Juan, Michoacán”, *Madera y bosque*, 7(2), 27-49.

Palahi, M., Pukkala, T., Miina, J. and Montero, G. (2003) “Individual-tree growth and mortality models for Scots pine (*Pinus silvestris* L.) in north-east Spain”, *Ann. For. Sci*., (in press)

Pardé, J. (1980) “Forest biomass”, *Forestry abstract (Review article),* 41(8), 343-362.

Río, M. and Montero, G. (2001) “Modelo de simulación de claras en masas de Pinus *sylvestris* L.”, *Monografías INIA: Forestal* nº 3, 114 pp.

Rojo, A. and Montero, G. (1996) *El pino silvestre en la Sierra de Guadarrama*. Ministerio de Agricultura, Pesca y Alimentación, Madrid.

Valinger E. (1993) “Effects of thinning and nitrogen fertilization on growth of Scots pine trees: total annual biomass increment, needle efficiency, and aboveground allocation of biomass increment”, *Can. J. For. Res.*, 23, 1639-1644.