Growth and Yield Models for *Pinus halepensis* Mill.

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SUMMARY

Growth and yield models of silviculture applied to four site indices have been drawn up. The data were obtained in 72 plots, installed in 1965 in man made stands of *Pinus halepensis* Mill., and inventoried in 1965, 1975, 1980, 1988 y 1999. The site index was defined as the top height at age 80 and models were adjusted using the Richards function, obtaining four site qualities: 20, 17, 14 and 11. Following this, silvicultural production models, including two different thinning regimes, were developed for the two higher site qualities sites, with more productive interest (20 and 17) using a simulation with the Hart-Becking rate. For 11 and 14 site quality, only one moderate thinning regime was developed, bearing in mind their most important protection value.

KEY WORDS: *Pinus halepensis*
Site quality
Growth and yield models
Yield tables
Silviculture
Spain

INTRODUCTION

Pinus halepensis Mill. plays an important role in the ecology and landscape of the Mediterranean basin. This pioneer and undemanding species is easily regenerated and capable of colonizing very poor and degraded soils. It is an essential component in reforestation strategy for limy soils in the arid or semi-arid climates of the Mediterranean basin, due both to its intrinsic ability to colonize and to its effect in improving soils and microclimates, thus in turn favouring the growth of broadleaf Mediterranean species *(Quercus ilex* L., *Q. coccifera* L. y *Q. faginea* Lamk.*)* within its stands (Quezel, 1986). It often forms mixed stands consisting of an upper storey of *P. halepensis* and an understorey

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formed by one of the above species, usually evergreen or kermes oak (Gandullo 1972; Pavari, 1954; Plaisance, 1978; Senni, 1931).

In Spain, *Pinus halepensis* occupies 1,046,978 ha in single-species stands, and 497,709 ha in mixed stands, of which 229,678 ha are with *Pinus nigra* Arn. ssp. *salzmanii,* 183,184 ha with *Pinus pinaster* Ait. and 84.847 ha with *Quercus ilex.* In the second forest national inventory (IFN, 1998) the area mixed with *Q. coccifera* is not registered, because this species is considered as an underbrush species. Stands produced by reforestation are estimated at almost 600,000 ha.

P. halepensis stands have a very diversified structure as a rule, and understanding of this is necessary in order to explain their silviculture. Roughly speaking we can divide *P. halepensis* woodland into three broad categories (Nahal, 1962; Panetsos, 1981; Kadik, 1983; Gómez Manzaneque, 1997):

– Even-aged stands resulting from reforestation on soils of differing physical and chemical characteristics, but usually limy and of low fertility. Production models can be applied to these without great difficulty, providing guidelines for thinning. Where thinning is not carried out, sometimes because of lack of information or regulations concerning thinning, or because of its unprofitablilty, the result may be a slowing down of stand growth.
– Even-aged woodland resulting from forest fires. These usually consist of very dense stands –often with 10,000 or 12,000 trees/ha or more, even in mature stands. Delays in carrying out the first thinning in many of these stands, or the great length of the rotation period slow down growth and lead to a degeneration or depression of the stand. Here it is also necessary to develop a programme of silvicultural treatments designed to even out the density and to favour normal stand development.
– Natural stands with varying degrees of silvicultural intervention. These stands are complex in structure. They cannot be clearly categorized as even- or uneven-aged, and it is therefore inappropriate to apply a given silvicultural treatment which is based on such categorization. Such stands are formed by groups of one or two age classes, leading to an apparently of uneven-aged structure, and above all uneven surface distribution, with numerous clearings invaded by scrub, grassland and other species such as evergreen and kermes oak. Density is usually low, though there are always dense even-aged groups, mixed with scrubby clearings or heavily-thinned pinewood, which often end up as isolated trees within dense scrub. In such areas forest fires enable the pinewood to recover surface area and serve to produce stands of more even age and density.

Yiled models for a given species try to describe the evolution of the main stand variables in relation to age, by means of various functions. Production models of variable silviculture are obtained if the stand has been thinned, and there is experimental record of its response to different intensities of thinning. These models describe the evolution of variables for the main stand before and after the thinning, the timber removed and the total volume. In the absence of solid experience in the response of the species to different thinning regimes, it is necessary to accept the risk of proposing untested models of variable silviculture, which, despite their being based on indices of proven efficiency for other species, may lead to errors, especially when there is little experience in the construction of production models, and little knowledge of the silviculture of this species.

Growth and yield models for variable silviculture indicate the silvicultural interventions to be carried out during the rotation, the approximate age of the stand in which these should be performed, and the results which may be expected according to the intensity of the interventions (Cañellas *et al.*, 2000; Montero *et al.*, 1999). The choice of greater or lesser intensity of silvicultural activity will depend on the objectives of the silviculturist and on the ecological characteristics of the woodland terrain. At the risk of stating the obvious, it is important to bear in mind that these are models, and, as such, are a more or less abstract simplification of a complex reality. The silviculturist should understand that, while these may at times provide very accurate guidelines for silvicultural interventions throughout the rotation, they are not a strict and fixed set of rules.

All these models for tree species should be based on a system of quality classes using as a basic variable the age and dominant height of the population. In Spain, Erviti (1991) developed growth and yiled models for *Pinus halepensis,* based on site quality curves using the Richards (1959) function. At the same time he presented and estimation of productivity and a model of stand structure. Pita (1965) also developed stand quality curves for *Pinus halepensis* in Spain, using the Hossfeld model.

With a view to obtaining a useful tool for the silviculture of Spanish stands of *P. halepensis,* production models have been made of the silviculture found for different site qualities, as well as production models of variable silviculture, including thinning regimes –moderate and heavy– for the two most productive qualities.

MATERIAL AND METHODS

Description of the sample

The data used for this study are taken from the network of 72 experimental plots laid out in 1965, covering a wide range of ages and site qualities. The plots were established in the provinces of Albacete (10 plots), Castellón (3 plots), Jaén (5 plots), Murcia (19 plots), Teruel (3 plots), Valencia (22 plots) and Zaragoza (10 plots). No plots were established in Cataluña or the Balearic islands. Figure 1 shows the location of each plot. Table 1 shows the distribution of the plots according to age and site quality.

The plots are rectangular, with size varying between 750 m^2 and 2,500 m^2, depending on their age and density in order to obtain measurements for a minimum number of trees, in accordance with the methodology of Hummel *et al.* (1959).

Six inventories were carried out in 1965, 1970, 1975, 1980, 1988 and 1999. It was not possible to complete the six inventories in some plots, because of forest fires, or due to their reaching the end of their rotation and having been felled. The sixth inventory was carried out in 28 plots.

At the outset, trees in each plot were identified and numbered, and in each inventory the following data were recorded:

- Diameter at 1.3 m, in two perpendicular directions, of all the trees in the plot.
- Total height of a sample of 30 trees selected proportionally through the diameter range. Heights of the ten broadest trees were measured in order to enable the calculation of the dominant height.

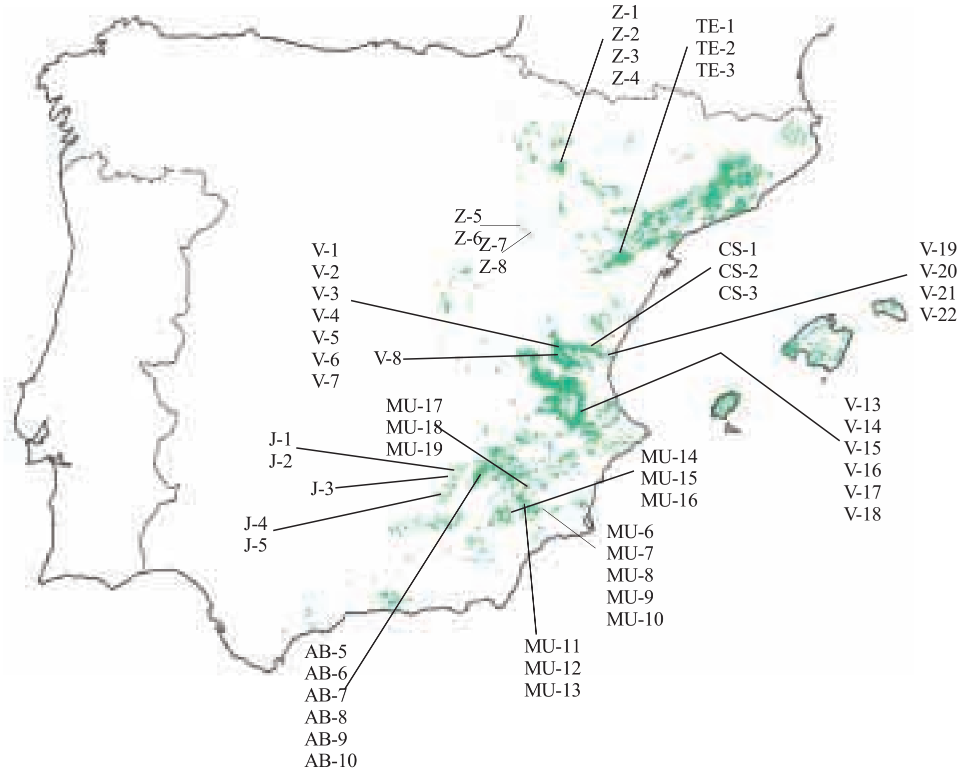

Fig. 1.–Location of permanent plots and stand distribution of *Pinus halepensis*

Table 1

Plot distribution according to age class and site index [1]

Age classes (years)	Number of plots by site index			
	Quality 20	Quality 17	Quality 14	Quality 11
< 20	1	1	1	–
20-30	2	2	6	1
30-40	1	2	5	3
40-50	1	4	4	5
50-60	1	3	10	9
60-70	1	1	2	2
70-80	–	1	–	1
80-90	–	–	1	1
TOTAL	7	14	29	22

(1) The plots are 35 years older than in the installation year and during this period six inventories have been elaborated in the years 1965, 1970, 1975, 1980, 1988 y 1999.

Data processing

The data obtained in each inventory were processed separately for each plot. The temporal variation of the main stand variables is shown in a summary table for each plot which schematically records its biometric and silvicultural evolution. These variables are defined for the main stand before thinning, for the removed crop, and for the main stand after thinning: number of trees per hectare, mean diameter, mean height, top height, basal area, volume by hectare and mean tree volume. Total volume and total basal area were calculated in each inventory for the whole stand.

Table 2 shows, as an example, one of these summaries – in this case plot number 11, in Murcia. The main variables for the stand before and after thinning can be seen, as can the material removed and the total volume for each of the inventories carried out.

Development of site index

With the data for top heights in each plot, site quality curves were developed, using the Richards (1959) model:

$$H_0 = a \cdot (1 - e^{-bt})^{1/c}$$

where Ho is top height; t is age in years; a, b, c are parameters of the model.

From the guide curve, anamorphic curves are drawn, defined by the top height reached at a typical age (García, 1983, 1984), which, in the case of *Pinus halepensis,* is regarded as 80 years (Montero *et al.,* 2000).

Growth and yield models based on the existing silvicultural conditions

In preparing these models, the following procedure was followed:

Using the top height (H_0) the number of trees per hectare for each site quality and age was calculated: $N = f\ (H_0)$

Various models were tested:

$$\text{Ln (n)} = a \cdot b \cdot H_0$$

$$\text{Ln (n)} = a \cdot b \cdot \text{Ln } (H_0)$$

$$\frac{100}{\sqrt{N}} = a + b \cdot H_0^c$$

$$\frac{100}{\sqrt{N}} = a + b \cdot H_0 \cdot t^c$$

Given N and (H_0), the quadratic mean diameter (D_g) was calculated:

$$D_g = f\ (H_0, N)$$

Table 2

Plot summary showing the stand evolution and silvicultural interventions that have been made. Mu-11 plot. Mean data by hectare

INV	Age years	S (ha)	MAIN CROP BEFORE THINNING							CROP REMOVED							MAIN CROP AFTER THINNING							TOTAL CROP	
			N	Dg	Hg	Ho	G	V	Vm	N	Dg	Hg	G	V	Vm	N	Dg	Hg	Ho	G	V	Vm	GT	VT
1	49	0.15	773	19.3	10.5	12.1	22.5	37.6	48.6	0	0	0	0	0	0	773	19.3	10.5	12.1	22.5	37.6	48.6	22.5	37.6
2 *	54	0.15	773	20.4	11.2	12.8	25.2	69.7	90.1	266	17.4	10.5	6.3	53.2	199.9	507	21.8	11.5	18.9	18.9	54.4	107.2	25.2	107.5
3	59	0.15	507	24.0	12.0	13.4	22.9	83.1	164.0	7	11.8	9.5	0	0.6	53.6	500	24.1	12.1	22.8	22.8	83.1	166.3	29.2	136.9
4	64	0.15	500	25.9	12.5	13.6	26.4	106.9	213.7	7	22.2	12.2	0.3	1.5	214.8	493	26.0	12.5	26.1	26.1	106.4	215.9	32.7	161.8
5	72	0.15	493	27.6	13.1	13.9	29.5	131.2	266.1	0	0	0	0	0	0	493	27.6	13.1	29.5	29.5	131.2	266.1	36.1	186.5
6	83	0.15	493	29.8	13.9	15.1	34.4	171.2	347.2	26	19.7	11.5	0.8	4.3	163.5	477	30.3	14.0	34.4	34.4	155.5	326.1	41.0	215.1

* A thinning was made in the second inventory. The other crop removed was due to natural mortality.

INV: inventory; S: plot area; N: stem number by hectare; Dg: squared mean diameter (cm); Hg: mean height (m); Ho: top height (m); G: basal area ($m^2 \cdot ha^{-1}$); V: volume ($m^3 \cdot ha^{-1}$); Vm: volume of mean tree ($dm^3 \cdot stem^{-1}$); GT: total basal area; VT: total volume.

Two models were tested:

$$Dg = a + b \cdot \frac{100}{\sqrt{N}} + c \cdot H_0$$

$$Dg = a + b \cdot \frac{100}{N^c} + d \cdot H_0$$

Both of them have been used in previous studies for production models of Spanish conifers (Rojo and Montero, 1996; Erviti, 1991).

The mean height (H_g) is calculated in relation to the top height (H_0): the most widely used model is the linear one, adjusting the values of parameters *a* and *b* by least square.

$$H_g = a + b \cdot H_0$$

Mean tree volume is obtained by using a double-entry table (Martínez-Millán *et al.*, 1993), and the volume per hectare as the product of the number of trees per hectare by the mean tree volume per age and site quality.

$$V_m = 0.077186 \cdot d^{1.84818} \cdot h^{0.88012}$$

$$R^2 = 0.9507$$

Where *Vm* is the mean gross tree volume with bark (dm^3); *d* is the normal diameter with bark (cm); *h* total height (m).

Development of growth and yield models for variable silviculture

In order to calibrate density in the models proposed here, the Hart-Becking index (Wilson, 1979), or relative spacing, was be used for stands which, due to their natural origin or their having been naturalised or resulting from plantations of high initial density, have an irregular, non-geometric surface distribution of trees. This index is defined as the relationship between the mean spatial distance between trees and the top height of the stand, expressed as a percentage. The following expression is used to determine this index:

$$S = \frac{10^4}{H_0 \cdot \sqrt{0.933 \cdot N}}$$

Where S is the Hart-Becking index; H_o is the top height (m); *N* is the number of trees per hectare.

The density (Table 4) was defined by varying the Hart-Becking index according to age and quality using the following criteria:

- on general knowledge of the silviculture of *Pinus halepensis,* which recommends strong and early thinning in order to arrive at a final density at between 40 and 60 years, according to site quality (Ciancio, 1986; Bedel, 1986)
- bearing in mind the work of Pardé (1957), Castellani *et al.* (1982), Franz and Forster (1980) and Couhert and Duplat (1993) on yield tables for this species

RESULTS

Site quality curves

The equation resulting from the mean or guide curve is as follows:

$$H_0 = 1.521453 \cdot (1 - e_{-0.203954 - t})^{1/1.046295} \quad [1]$$

There are four anamorphic curves proceeding from the guide curve, each separated at the age of 80 years by 3 m. Qualities adjusted were: quality 20, quality 17, quality 14 and quality 11; showing that at 80 years of age the corresponding top heights reach 20, 17, 14, and 11 m respectively. There are lower site qualities in the *Pinus halepensis* woodland, but their low productivity does not warrant sampling or the development of yield tables; silviculture there should be limited to conservation, restoration and fire prevention. When thinning is for some reason considered necessary, the model for quality 11 may be used as a general guide.

In modifying the guide curve in order to make it pass through the 80-year point, the values of parameters *b* and *c* of the Richards equation are maintained, modifying the local parameter *a,* which takes the following values according to quality:

QUALITY 20: $a_{20} = 2.532460$

QUALITY 17: $a_{17} = 2.152591$

QUALITY 14: $a_{14} = 1.772722$

QUALITY 11: $a_{11} = 1.392853$

By means of these equations the top height for each site quality and age can be calculated. The evolution of the top height by site qualities is shown in Figure 2.

Models based on the existing silvicultural conditions for *Pinus halepensis* Mill.

Using the top height (H_0), the number of trees per hectare for each site quality and age was calculated. The equations that showed the best adjustment was chosen among many others tested:

$$\text{Ln}(N) = 9.40793 - 1.16872 \cdot \text{Ln}(H_0) \quad [2]$$

$$R^2 = 0.598$$

The regression coefficient (R^2) in this adjustment is low, undoubtedly due to the lack of intervention in the test plots over the last thirty years. This gives rise to the fact that plots with the same H_0, not varying in density, differ greatly in their number of trees per hectare. In spite of the great variations in density, the large number of plots, many of which have six inventories, the previous model has represented fairly good the mean tendency of variation in the number of trees per hectare in relation to the dominant height.

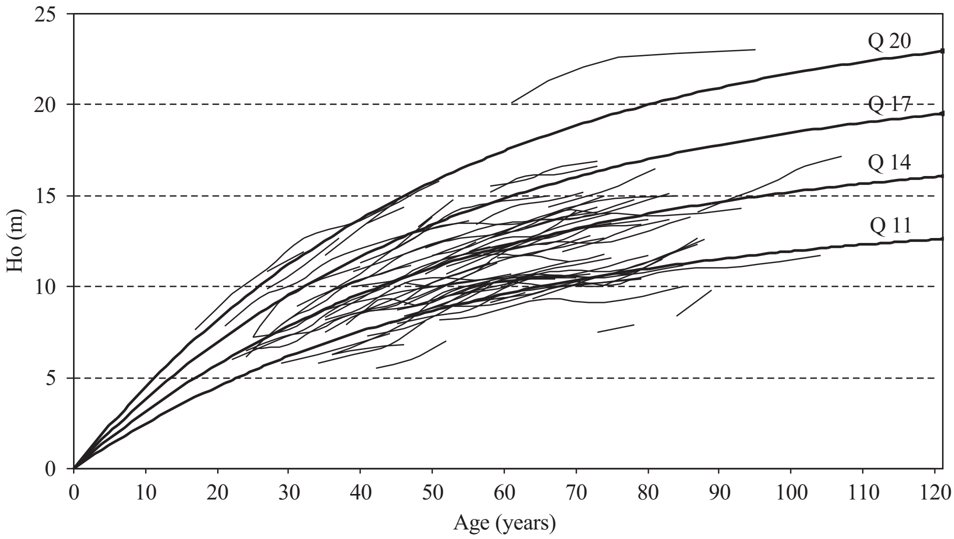

Fig. 2.–Site index for *Pinus halepensis*

The quadratic mean diameter (D_g) was calculated using the following equation:

$$D_g = -7.30304 + 1.18309 \cdot H_0 + 3.63489 \cdot \left(\frac{100}{N}\right) \quad [3]$$

$$R^2 = 0.598$$

The mean height (H_g) was calculated in relation to the top height (H_0) in the following way:

$$H_g = -0.57881 + 0.910849 \cdot H_0 \quad [4]$$

$$R^2 = 0.924$$

Adjusting the field data of all plots by means of equations [2], [3] and [4], and with figures obtained for the basal area (G) and the timber volume (up to 7 cm top diameter and not including the stump) the models for the existing silviculture were obtained for each quality (Table 3).

Table 3

Evolution of the main stand variables for *Pinus halepensis* in Spain

QUALITY 20 (H_0 = 20 m at 80 years)

AGE	Ho	N	Hg	Dg	G	V	Vm
20	8.2	1045	6.9	13.5	15.0	54.2	51.8
30	11.2	723	9.6	19.4	21.3	98.2	135.9
40	13.7	571	11.9	24.0	25.9	139.2	243.6
50	15.8	485	13.8	27.8	29.4	175.4	361.6
60	17.5	431	15.3	30.8	32.0	206.8	480.2
70	18.9	394	16.6	33.2	34.2	233.6	593.4
80	20.0	368	17.6	35.2	35.8	256.3	697.5
90	20.9	348	18.5	36.9	37.2	275.4	790.8
100	21.7	334	19.2	38.2	38.2	291.4	873.0
110	22.4	323	19.8	39.3	39.1	304.7	944.3
120	22.9	314	20.3	40.2	39.8	315.7	1005.5

QUALITY 17 (H_0 = 17 m at 80 years)

AGE	Ho	N	Hg	Dg	G	V	Vm
20	6.9	1264	5.8	11.1	12.1	38.6	30.5
30	9.5	874	8.1	16.2	18.0	73.0	83.5
40	11.7	691	10.0	20.2	22.2	105.2	152.3
50	13.4	587	11.6	23.5	25.4	133.9	228.2
60	14.8	521	12.9	26.1	27.9	158.8	304.9
70	16.0	476	14.0	28.2	29.8	180.1	378.3
80	17.0	444	14.9	30.0	31.3	198.1	445.9
90	17.8	421	15.6	31.4	32.6	213.3	506.6
100	18.5	404	16.2	32.5	33.6	226.0	560.0
110	19.0	390	16.7	33.5	34.4	236.6	606.4
120	19.5	380	17.1	34.3	35.0	245.4	646.3

QUALITY 14 (H_0 = 14 m at 80 years)

AGE	Ho	N	Hg	Dg	G	V	Vm
20	5.7	1586	4.6	8.5	9.0	24.7	15.6
30	7.8	1097	6.6	12.9	14.3	49.9	45.5
40	9.6	867	8.2	16.3	18.1	73.9	85.3
50	11.0	736	9.5	19.1	21.0	95.5	129.8
60	12.2	653	10.6	21.3	23.3	114.3	174.9
70	13.2	597	11.4	23.1	25.0	130.4	218.3
80	14.0	558	12.2	24.6	26.4	144.1	258.4
90	14.7	528	12.8	25.8	27.5	155.6	294.5
100	15.2	506	13.3	26.7	28.5	165.2	326.3
110	15.7	489	13.7	27.6	29.2	173.3	354.0
120	16.0	476	14.0	28.2	29.8	180.0	377.8

QUALITY 11 (H_0 = 11 m at 80 years)

AGE	Ho	N	Hg	Dg	G	V	Vm
20	4.5	2103	3.5	5.9	5.7	12.9	6.1
30	6.2	1454	5.0	9.4	10.2	29.5	20.3
40	7.5	1149	6.3	12.3	13.5	45.9	40.0
50	8.7	976	7.3	14.5	16.1	60.9	62.4
60	9.6	866	8.2	16.3	18.1	74.0	85.4
70	10.4	792	8.9	17.8	19.7	85.3	107.7
80	11.0	739	9.4	19.0	20.9	94.9	128.4
90	11.5	700	9.9	20.0	21.9	103.0	147.1
100	11.9	671	10.3	20.8	22.7	109.8	163.6
110	12.3	649	10.6	21.4	23.4	115.5	178.0
120	12.6	631	10.9	22.0	23.9	120.2	190.4

Ho: top height (m); N: stem number by hectare; Hg: mean height (m); Dg: squared mean diameter (cm); G: basal area ($m^2 \cdot ha^{-1}$); V: volume ($m^3 \cdot ha^{-1}$); Vm: volume of mean tree ($m^3 \cdot stem^{-1}$).

Yield models for variable silviculture of *Pinus halepensis*

The models for variable or proposed silviculture present the evolution of the stand after the application of two intensities of simulated thinning, by means of the Hart-Becking index (Table 4), taking into account the number of trees, at age 20, found in the test plots for the four defined site qualities.

Table 4

Hart-Becking rate as a function of age and site index

AGE CLASSES	MODERATE THINNINGS				HEAVY THINNINGS	
	Quality 20	Quality 17	Quality 14	Quality 11	Quality 20	Quality 17
20	42	42	47	51	42	42
20-30	36	37	36	38	39	39
30-40	36	37	34	38	39	39
40-50	34	34	30	34	37	35
50-60	34	32	30	34	37	32
60-70	32	30	30	34	35	32
70-80	32	30	30	34	35	32
80-90	32	30	30	34	35	32
90-100	32	30	30	34	35	32
100-120	32	30	30	34	35	32

In qualities 14 and 11 a single silvicultural model is proposed, with a moderate thinning regime. In stands of this quality, with low timber yield and high protective and ecological value, it is not usually suitable to adopt more intensive silvicultural regimes which might lower the protective capacity.

The intensity of the thinning regime is characterized by the number of trees extracted through the whole rotation period, and by the time and rotation of thinning. The final density of trees/ha varies relatively little between different thinning regimes, but the effect of these on the diameter reached at the end of the cycle, and hence on the quality and price of the final products, can be important.

These models show a gradual lowering of the numbers of trees, with small gains produced artificially at ten year periods, as a result of having chosen this time interval for its application, but these intervals do not need to be rigidly adhered to by the silviculturist in planning and carrying out interventions. In practice interventions for this species should be carried out at least every 15 years if they are to be viable financially. In high quality stands this period can be less at younger age, and be raised to 20 or more years in thinning stands over 50 or 60 years old.

Figure 3 shows graphically the evolution in the number of trees per hectare before and after thinning. A band of varying width is obtained, within which it should be attempted to maintain the stand. The exact ages for thinning, the number of thinnings and the weight of a given thinning may vary considerably according to the judgement of the silviculturist.

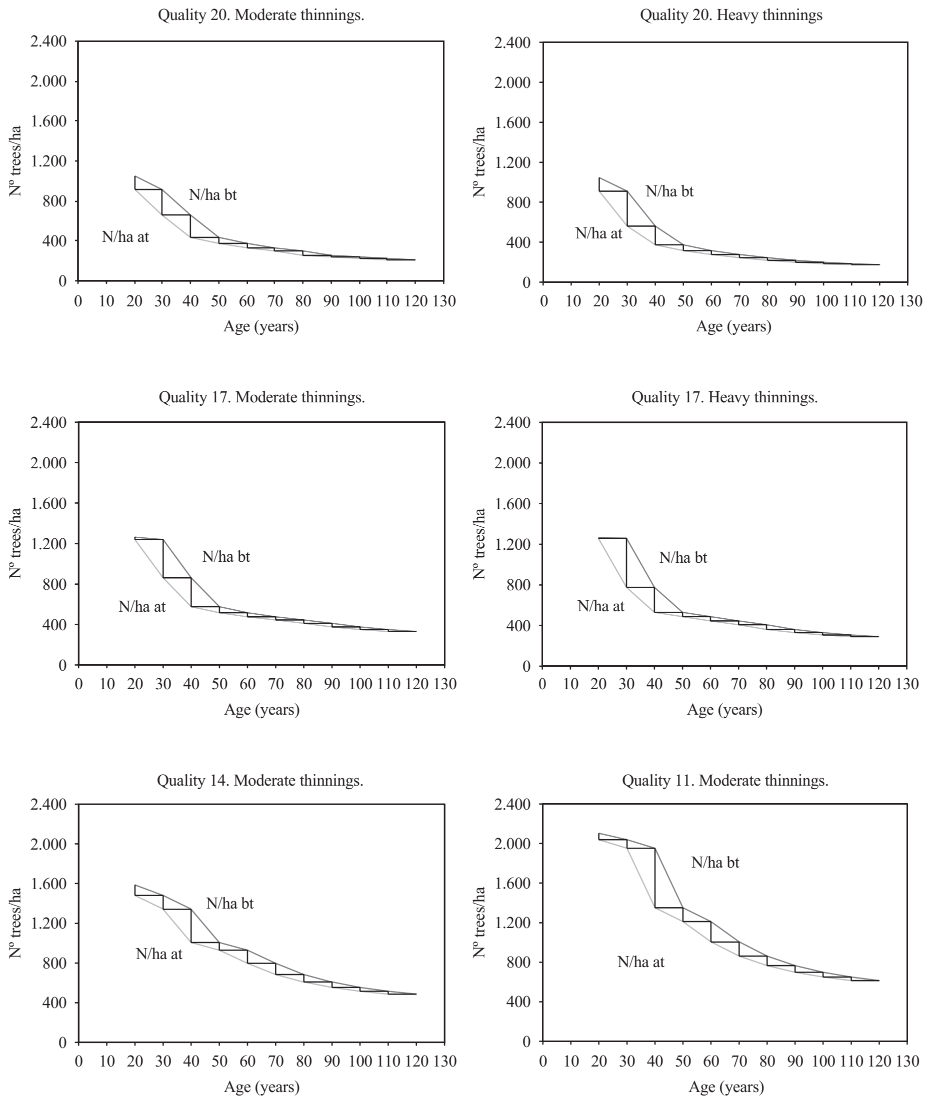

Fig. 3.–Density (tree · ha^{-1}) before and after thinning for site quality and thinning regimes for *Pinus halepensis*

(N/ha bt, N/ha at: Tree number by hectare before and after thinning.)

The graphic representation of the basal area (Fig. 4) and volume (Fig. 5) of the main stand after thinning, together with the basal area and volume, total and removed, during thinning, provide useful information for forest management and enable rapid and schematic comparisons to be made of the evolution of these important stand variables, according to site quality, thinning regime and stand age.

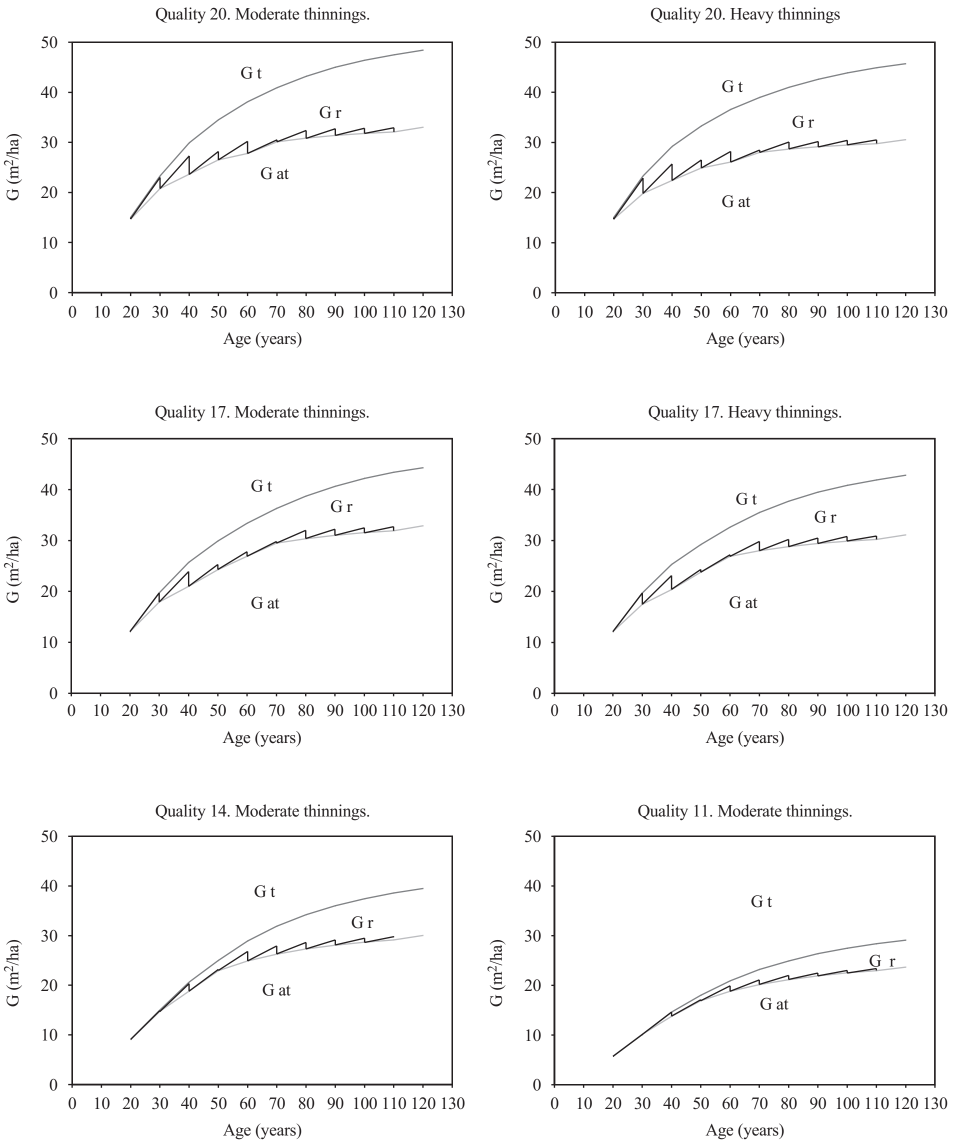

Fig. 4.–Basal area ($m^2 \cdot ha{-}1$) of main stand after thinning, basal area remove with thinning and total basal area for site quality and thinning regimes for *Pinus halepensis*

(Basal area: GT: total; Gr: removed; Gat: after thinning.)

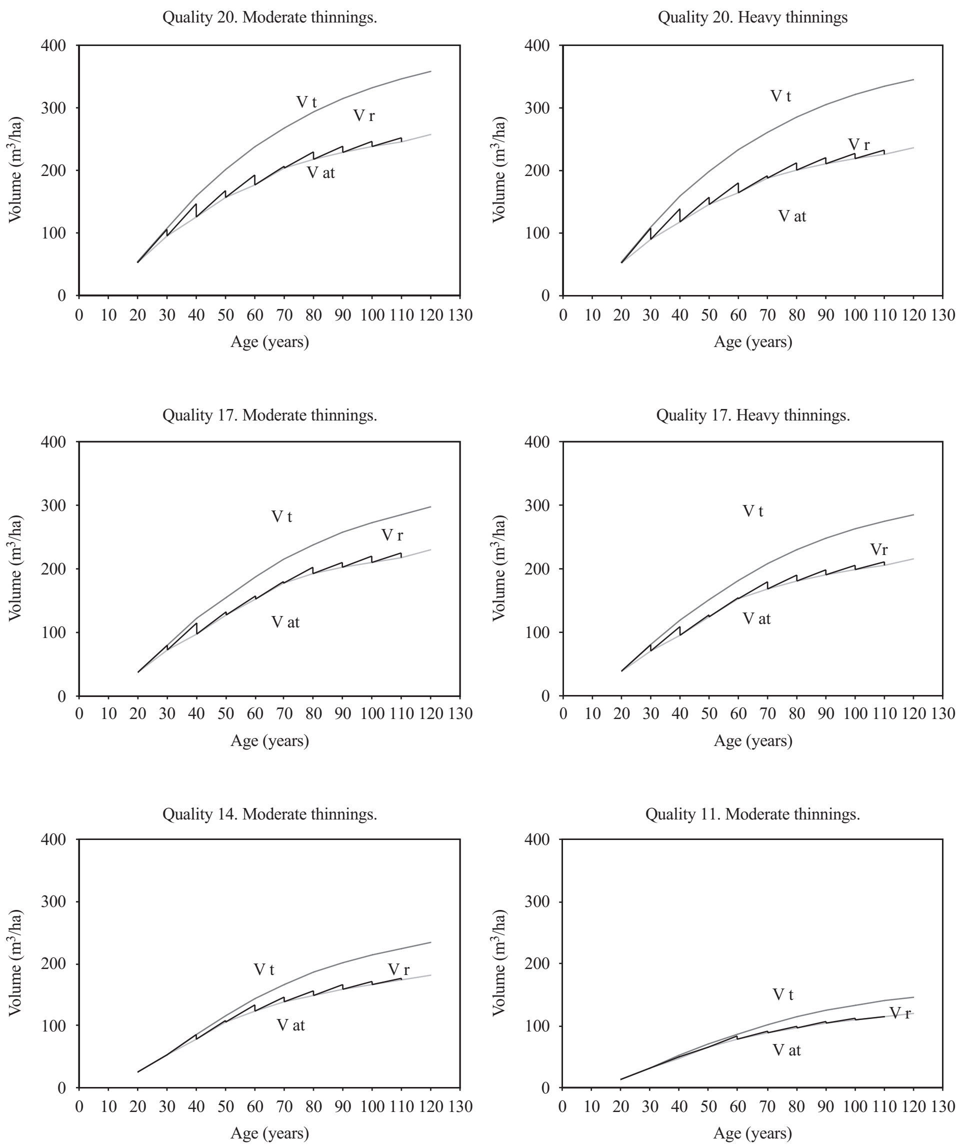

Fig. 5.–Volumen ($m^3 \cdot ha{-}1$) of main stand after thinning, volume remove with thinning and total volume for site quality and thinning regimes for *Pinus halepensis*

(Volume: Vt: total; Vr: removed; Vat: after thinning.)

DISCUSSION

Site quality curves

A comparative study was made of the quality curves developed in this study and those in other work on *Pinus halepensis* stands, both in Spain and elsewhere in its range of distribution.

The quality curves adjusted in this study reach a lower height than those presented by Pita (1965) for the first three site qualities which can be considered equivalent to our qualities 20, 17 and 14. Pita's quality IV, which reaches a top height slightly over 7 m at 70 years, was not taken into account in the present study, although we have defined a quality 11 slightly inferior to his quality III. These variations, and the fact that the latter curves were drawn on the sole basis of data from the first inventory for this network of plots (whereas we used data from up to six inventories are available) makes it difficult to establish an objective comparison of the evolution of top heights, which are also adjusted by different mathematical models.

The curves presented by Pardé (1957) for the communal forest of Gémenos include the evolution of mean height between 30 and 75 years. These are also difficult to be compared because of both the short time involved and the method of construction. In general heights shown in Pardé (1957) are considerably higher than in the present study.

Franz and Forster (1980) present quality curves for this species in Tunisia. They define 13 qualities separated by one meter in top height at an age of 100 years, and vary between 8 m for the lowest quality and 20 m for the highest. The data were taken from a network of 1,500 temporary plots, and from the stem analyses of 200 trees. Their evolution and form coincide basically with those obtained in the present study of Spanish stands, though the top height at 80 years does not reach 18 m in the first quality, placing it a little below our quality 20.

Castellani *et al.* (1982) present five quality curves for *Pinus halepensis* in Italy, in which a greater height growth can be seen, specially in the early years, exceeding 20 m top height at age 40 in the first quality and slowing down in height growth from this age.

Quality curves for Israel (Röhle, 1992) have 10 qualities separated by top height at 50 years in intervals of two meters, from the lowest quality, reaching 8 m, to the top quality, reaching 28m top height at this age. These qualities are hard to find in the western Mediterranean, with the exception of small stands in special sites which, due to their small size are not usually included in production models for the species.

Couhert y Duplat (1993) present curves for ten site qualities of *Pinus halepensis* in the French region of «Provence-Alpes-Costa Brava». Defined by top height at 50 years these are separated into ten qualities at two-meter intervals between 4 m and 18 m. At 80 years the top quality is 2.5 m higher than the top height of quality 20 defined in this study of Spanish stands.

Finally, Erviti (1991) defines five site qualities, based on the same network of plots, and which differ from those presented in the present study in that the author added to the Richards model the modification proposed by García (1980, 1983), which consists of addings at the end a stochastic term capable of resolving differences which may have arisen from the sampling method. The reason for this second term is explained by García (1983) in maintaining that growth cannot be represented exclusively by a deterministic equation (that of Richards), owing to its relation to random factors in the environment.

Some authors (Ortega and Montero, 1984; Rojo and Montero, 1996) have since doubted the usefulness of including this statistical term, as it presents difficulties when making adjustments, and may not noticeably improve the results. The present study reaches similar conclusions.

Models based on the existing silvicultural conditions for *Pinus halepensis* Mill.

In this network of permanent plots no silviculture characterised by one defined thinning regime was applied. In the second inventory (1979), moderate thinning was carried out by taking out the number of trees per hectare considered necessary for the purpose of bringing the stand to a suitable density for its age and diameter. Since 1970 there has been no thinning, resulting in a density higher than normal for such stands. It also needs to be borne in mind that the plots were chosen from dense uniform stands in order to arrive at the best estimate for total production of the species.

We can thus state that the growth models based on the existing silvicultural conditions which we present below, show a higher density than the mean density for even-aged stands subject to silvicultural treatment by the forestry services or private owners. Although they do not represent a given type of silviculture, we believe that the models presented here offer valuable information on the development of total production and basal area in dense stands, with their respective mean and current increments, which may be very useful for managers of these pinewoods, as well as serving as a basis for the construction of models of variable silviculture.

These tables should be regarded as a silvicultural description of the stands arrived at by means of determining and quantifying the main stand variables. Since no thinning programme was applied to the available plots over a 35 year period, it was not possible to calculate the timber removed. The normal decrease in the number of trees per hectare with age is a result of one thinning carried out in 1970, at the time of the second inventory, of the natural mortality throughout the period, and of the silviculture applied in each plot before it was laid out.

Yield models for variable silviculture of *Pinus halepensis* Mill.

From a silvicultural and ecological point of view, silvicultural interventions should be careful, moderate and frequent. Heavy and infrequent thinnings are, however, more economical. A practical silviculture should be based on an attempt to find a compromise between these two extremes, bearing in mind that the ecological and protective factors, with the need to ensure conservation, stability and diversity, should be paramount, rather than productive or economic factors.

The mean and current increments reached by *Pinus halepensis* stands in the Mediterranean area of Spain are relatively low, not because this is a slow-growing species but because as a rule the stands are situated on poor and degraded soils in arid or semi-arid climates which do not foster rapid growth in this or any other species.

The development of mean and current increment in volume (Fig. 6) shows that *Pinus halepensis* has a relatively rapid growth rate between 20 and 60 years.

In a species with high protective value, which, due to its characteristics and that of the environment in which it grows, does not produce individuals of great size at the end of

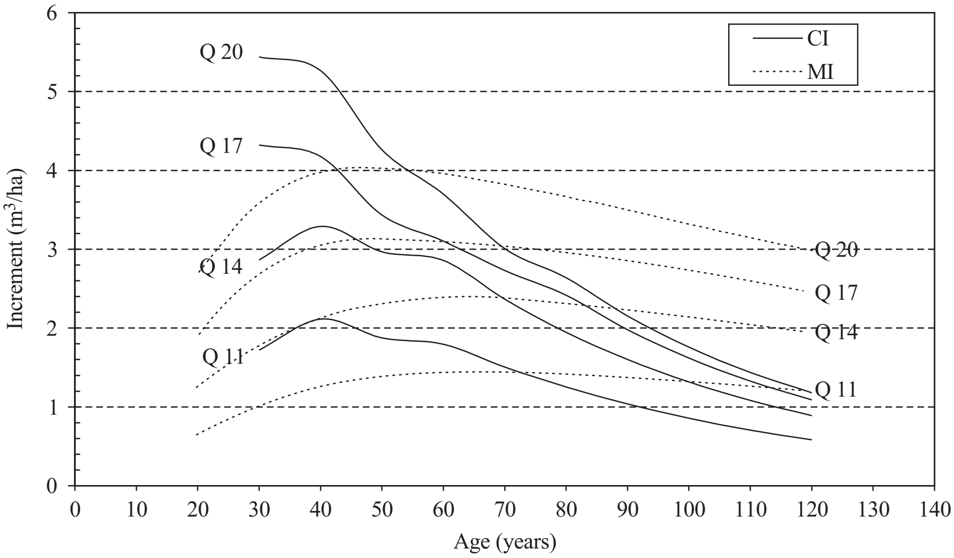

Fig. 6.–Current and annual increment in volume in different site qualities for *Pinus halepensis*

its rotation period, the final density in number of trees per hectare varies relatively little between one thinning regime and another. The most robust regimes will be those where the first thinnings have been heaviest, allowing the trees to develop with less competition, thereby reaching a higher diameter. If with such thinnings the final number of trees cannot be low, because of the important protective function of all *P. halepensis* stand, then the fellings carried out at 50-60 years cannot be intensive. Thus in this thinning regime we have taken out many low diameter trees in the first stages, but will be able to take out few trees in later thinnings or improvement cuttings.

In a regime of moderate thinning, the number of low diameter trees taken out in the first clearings is lower and, as a result, there are more trees to be removed in later thinnings and in improvement or preparatory cuttings.

If the number of trees reaching the end of rotation cannot be very different because the need for soil protection does not allow for very low densities, even in the heaviest thinning regime, then it follows that in the second half of the rotation a few more trees can be removed in the moderate thinning regime than in the intensive. These trees will be somewhat broader than those removed in the first half of the rotation in the intensive thinning regime, which may mean that the total volume removed in the moderate thinning regime will be equal to or greater than that taken out under the intensive thinning regime (Table 5).

The fact that there is a lack of experimental data on thinnings for this species makes it necessary to determine the moderate and intensive thinning regimes by means of the Hart-Backing index, and to estimate the number of trees in relation to the dominant height at certain ages. This method is less precise when estimating the total crop and the timber removed than those based on experimental plots with thinning regimes.

Table 5

Yield table for *Pinus halepensis* in Spain

Quality 20. Moderate thinnings

AGE (years)	Ho	MAIN CROP BEFORE THINNING					CROP REMOVED				MAIN CROP AFTER THINNING				TOTAL CROP		
		N	Hg	Dg	G	V	N	Dg	G	V	N	Dg	G	V	VT	Im	Ic
20	8.2	1045	6.9	13.5	15.0	54.2	136	5.6	0.3	1.4	909	14.3	14.7	52.5	53.9	2.7	–
30	11.2	909	9.6	17.9	22.9	106.9	251	10.5	2.2	12.5	658	20.0	20.8	95.0	107.5	3.6	5.4
40	13.7	658	11.9	23.0	27.3	147.7	218	14.7	3.7	33.8	440	26.2	23.6	125.3	159.1	4.0	5.3
50	15.8	440	13.8	28.6	28.2	167.9	67	18.2	1.7	44.9	373	30.1	26.5	156.4	201.2	4.0	4.3
60	17.5	373	15.3	32.1	30.2	193.4	69	20.9	2.4	61.1	304	34.1	27.8	176.6	237.6	4.0	3.7
70	18.9	304	16.6	35.8	30.5	206.6	10	23.1	0.4	64.0	294	36.1	30.1	203.6	267.6	3.8	3.0
80	20.0	294	17.6	37.5	32.4	230.0	33	24.9	1.6	76.0	262	38.7	30.8	217.5	293.6	3.7	2.6
90	20.9	262	18.5	39.9	32.6	239.0	23	26.5	1.3	85.9	239	40.9	31.4	228.8	314.8	3.5	2.2
100	21.7	239	19.2	41.8	32.8	246.4	17	27.8	1.0	94.1	222	42.7	31.8	238.0	332.1	3.3	1.8
110	22.4	222	19.8	43.5	32.9	252.4	12	28.9	0.8	100.7	209	44.2	32.1	245.5	346.2	3.1	1.4
120	22.9	209	20.3	44.8	33.0	257.3	–	–	–	–	–	–	–	–	358.0	3.0	1.2

Quality 20. Heavy thinnings

AGE (years)	Ho	MAIN CROP BEFORE THINNING					CROP REMOVED				MAIN CROP AFTER THINNING				TOTAL CROP		
		N	Hg	Dg	G	V	N	Dg	G	V	N	Dg	G	V	VT	Im	Ic
20	8.2	1045	6.9	13.5	15.0	54.2	136	5.6	0.3	1.6	909	14.3	14.7	52.5	54.1	2.7	–
30	11.2	909	9.6	17.9	22.9	106.9	348	10.7	3.1	19.6	560	21.2	19.8	90.0	109.6	3.7	5.4
40	13.7	560	11.9	24.2	25.7	138.1	186	15.1	3.3	41.2	375	27.6	22.4	117.9	159.1	4.0	4.8
50	15.8	375	13.8	30.0	26.6	156.7	60	18.6	1.6	52.8	315	31.7	24.9	145.8	198.7	4.0	3.9
60	17.5	315	15.3	33.8	28.2	179.3	58	21.5	2.1	68.9	257	35.9	26.1	164.3	233.2	3.9	3.3
70	18.9	257	16.6	37.6	28.5	191.4	11	23.8	0.5	72.7	246	38.1	28.0	187.9	260.6	3.7	2.7
80	20.0	246	17.6	39.4	30.1	211.5	27	25.5	1.4	84.5	219	40.8	28.7	200.5	285.1	3.6	2.4
90	20.9	219	18.5	42.0	30.2	219.8	19	27.2	1.1	94.2	199	43.1	29.1	210.8	305.0	3.4	1.9
100	21.7	199	19.2	44.0	30.4	226.5	14	28.5	0.9	102.2	185	45.0	29.5	219.1	321.3	3.2	1.6
110	22.4	185	19.8	45.7	30.5	232.0	10	29.7	0.7	108.7	175	46.5	29.8	225.9	334.6	3.0	1.3
120	22.9	175	20.3	47.2	30.6	236.4	–	–	–	–	–	–	–	–	345.1	2.9	1.1

Quality 17. Moderate thinnings

AGE (years)	Ho	MAIN CROP BEFORE THINNING					CROP REMOVED				MAIN CROP AFTER THINNING				TOTAL CROP		
		N	Hg	Dg	G	V	N	Dg	G	V	N	Dg	G	V	VT	Im	Ic
20	6.9	1264	5.8	11.1	12.1	38.6	6	3.0	0.0	0.0	1258	11.1	12.1	38.6	38.6	1.9	–
30	9.5	1258	8.1	14.1	19.7	81.8	396	7.7	1.8	8.3	862	16.3	17.9	72.7	81.0	2.7	4.3
40	11.7	862	10.0	18.8	23.9	114.4	286	11.3	2.9	23.2	576	21.5	21.0	98.6	121.8	3.0	4.2
50	13.4	576	11.6	23.6	25.2	132.9	60	14.3	1.0	28.7	516	24.5	24.3	127.2	155.8	3.1	3.4
60	14.8	516	12.9	26.2	27.8	158.2	41	16.4	0.9	34.0	475	26.8	26.9	152.7	186.6	3.1	3.1
70	16.0	475	14.0	28.2	29.8	179.9	11	18.1	0.3	35.9	464	28.4	29.5	178.0	213.8	3.1	2.7
80	17.0	464	14.9	29.6	31.9	202.1	52	19.6	1.6	46.3	412	30.6	30.4	191.3	237.6	3.0	2.4
90	17.8	412	15.6	31.6	32.3	211.1	36	20.9	1.2	55.0	376	32.4	31.0	202.2	257.2	2.9	2.0
100	18.5	376	16.2	33.2	32.5	218.4	26	22.0	1.0	62.2	349	33.9	31.5	211.0	273.1	2.7	1.6
110	19.0	349	16.7	34.5	32.7	224.3	20	22.9	0.8	68.1	330	35.1	31.9	218.1	286.2	2.6	1.3
120	19.5	330	17.1	35.6	32.9	229.0	–	–	–	–		–	–	–	297.1	2.5	1.1

Table 5 (continued)

Yield table for *Pinus halepensis* in Spain

Quality 17. Heavy thinnings

AGE (years)	Ho	MAIN CROP BEFORE THINNING					CROP REMOVED				MAIN CROP AFTER THINNING				TOTAL CROP		
		N	Hg	Dg	G	V	N	Dg	G	V	N	Dg	G	V	VT	Im	Ic
20	6.9	1264	5.8	11.1	12.1	38.6	6	3.0	0.0	0.0	1258	11.1	12.1	38.6	38.6	1.9	–
30	9.5	1258	8.1	14.1	19.7	81.8	482	7.7	2.3	10.3	776	16.9	17.5	70.5	80.7	2.7	4.3
40	11.7	776	10.0	19.4	23.0	109.9	257	11.5	2.7	24.1	519	22.4	20.4	95.1	119.2	3.0	3.9
50	13.4	519	11.6	24.4	24.3	127.4	32	14.5	0.5	27.1	487	24.9	23.8	124.3	151.4	3.0	3.2
60	14.8	487	12.9	26.6	27.1	154.3	12	16.5	0.3	28.6	475	26.8	26.9	152.7	181.3	3.0	3.0
70	16.0	475	14.0	28.2	29.8	179.9	68	18.3	1.8	40.1	408	29.6	28.0	168.0	208.1	3.0	2.7
80	17.0	408	14.9	30.7	30.2	190.3	45	19.9	1.4	49.6	362	31.8	28.8	180.5	230.1	2.9	2.2
90	17.8	362	15.6	32.8	30.5	198.7	32	21.3	1.1	57.5	330	33.7	29.4	190.5	248.0	2.8	1.8
100	18.5	330	16.2	34.4	30.8	205.5	23	22.4	0.9	64.0	307	35.2	29.9	198.7	262.8	2.6	1.5
110	19.0	307	16.7	35.8	31.0	211.0	17	23.4	0.7	69.4	290	36.4	30.2	205.4	274.8	2.5	1.2
120	19.5	290	17.1	37.0	31.1	215.5	–	–	–	–	–	–	–	–	284.9	2.4	1.0

Quality 14. Moderate thinnings

AGE (years)	Ho	MAIN CROP BEFORE THINNING					CROP REMOVED				MAIN CROP AFTER THINNING				TOTAL CROP		
		N	Hg	Dg	G	V	N	Dg	G	V	N	Dg	G	V	VT	Im	Ic
20	5.7	1586	4.6	8.5	9.0	24.7	105	3.0	0.1	0.2	1481	8.8	9.1	24.7	24.9	1.2	–
30	7.8	1481	6.6	11.3	15.0	53.3	139	4.7	0.2	1.2	1342	11.8	14.7	52.1	53.3	1.8	2.9
40	9.6	1342	8.2	13.9	20.3	85.0	336	7.6	1.5	8.2	1006	15.4	18.8	77.4	85.6	2.1	3.3
50	11.0	1006	9.5	17.1	23.2	107.1	29	9.9	0.2	9.3	977	17.3	23.0	105.9	115.2	2.3	3.0
60	12.2	977	10.6	18.7	26.8	134.5	180	11.7	1.9	19.7	797	19.9	24.9	123.6	143.3	2.4	2.9
70	13.2	797	11.4	21.1	27.9	147.2	113	13.3	1.6	28.7	684	22.1	26.3	137.9	166.6	2.4	2.4
80	14.0	684	12.2	23.1	28.6	157.4	76	14.7	1.3	36.3	608	23.9	27.3	149.5	185.7	2.3	1.9
90	14.7	608	12.8	24.7	29.1	165.5	53	15.8	1.0	42.6	554	25.4	28.1	158.9	201.5	2.2	1.6
100	15.2	554	13.3	26.0	29.5	172.0	39	16.7	0.9	47.9	515	26.6	28.6	166.5	214.5	2.1	1.3
110	15.7	515	13.7	27.1	29.8	177.3	29	17.4	0.7	52.4	486	27.6	29.1	172.8	225.1	2.0	1.1
120	16.0	486	14.0	28.0	30.0	181.6	–	–	–	–		–	–	–	234.0	2.0	0.9

Quality 11. Moderate thinnings

AGE (years)	Ho	MAIN CROP BEFORE THINNING					CROP REMOVED				MAIN CROP AFTER THINNING				TOTAL CROP		
		N	Hg	Dg	G	V	N	Dg	G	V	N	Dg	G	V	VT	Im	Ic
20	4.5	2103	3.5	5.9	5.7	12.9	65	2.5	0.0	0.1	2038	6.0	5.7	13.0	13.0	0.7	–
30	6.2	2038	5.0	8.0	10.1	30.2	86	3.0	0.0	0.3	1952	8.1	10.1	30.1	30.4	1.0	1.7
40	7.5	1952	6.3	9.8	14.6	51.2	647	4.0	0.8	3.6	1305	11.6	13.8	47.1	50.7	1.3	2.1
50	8.7	1305	7.3	12.9	17.1	65.8	72	6.1	0.2	4.5	1233	13.2	16.9	64.8	69.3	1.4	1.9
60	9.6	1233	8.2	14.3	19.9	82.7	227	7.7	1.1	9.3	1005	15.4	18.8	77.5	86.8	1.4	1.8
70	10.4	1005	8.9	16.3	21.1	92.5	143	9.0	0.9	13.7	862	17.3	20.2	87.8	101.5	1.5	1.5
80	11.0	862	9.4	18.0	21.9	100.3	96	10.2	0.8	17.6	766	18.8	21.2	96.1	113.8	1.4	1.3
90	11.5	766	9.9	19.4	22.6	106.5	67	11.1	0.6	21.0	699	20.0	21.9	102.9	123.9	1.4	1.0
100	11.9	699	10.3	20.5	23.0	111.5	49	11.8	0.5	23.8	650	21.0	22.5	108.5	132.3	1.3	0.9
110	12.3	650	10.6	21.4	23.4	115.6	37	12.4	0.4	26.2	613	21.8	23.0	113.0	139.2	1.3	0.7
120	12.6	613	10.9	22.2	23.7	118.9	–	–	–	–	–	–	–	–	145.0	1.2	0.6

Ho: top height (m); N: stem number by hectare; Hg: mean height (m); Dg: squared mean diameter (cm); G: basal area ($m^2 \cdot ha^{-1}$); V: volume ($m^3 \cdot ha^{-1}$); VT: total volume ($m^3 \cdot ha^{-1}$); Im: mean increment of volume ($m^3 \cdot ha^{-1} \cdot year^{-1}$); Ic: current increment of volume ($m^3 \cdot ha^{-1} \cdot year^{-1}$).

Italian yield tables (Castellani *et al.,* 1982) propose a rotation of 70 years. Table 6 shows data for mean diameter, the corresponding number of trees per hectare, top height, total volume at the end of rotation and mean maximum increment for each of the four qualities. It can be seen, according to this information, that the density is higher than that proposed for Spanish stands, and that the quality, yield and increment are much higher.

Table 6

Main data of some other yield table of *Pinus halepensis* to compare with Spanish yield table

	Castellani *et al.*, 1982				Franz and Forster, 1980	Röhle, 1992	Couhert and Duplat, 1993	Ciancio, 1986
Rotation period	70	70	70	70	80	70	60	40
Site index	1.ª	2.ª	3.ª	4.ª	16 m	1.ª	16 m	16 m
Dg	37.3	29.8	22.8	16.5	44	28.7	26.6	44
N.º stem/ha	332	479	780	1241	200	298	450	200
Ho	21.9	18.4	14.9	11.4	21	16.6	17.7	21
Total volume	472	250	229	113	462	175	173	440-480
Mean increment	17.9	13.0	6.6	2.1	5.8 (90 years)	2.9	–	5.8

Rotation period (years); Dg: squared mean diameter (cm); Ho: top height (m); Total volume ($m^3 \cdot ha^{-1}$); Mean increment ($m^3 \cdot ha^{-1} \cdot year^{-1}$).

The first quality in the Algerian production tables (Franz and Forster, 1980), with a 70 year rotation (Table 6) can be compared to quality 17 in our own tables, with an intensive thinning regime.

In the yield table for *Pinus halepensis* in Israel (Röhle, 1992), quality 16 is very similar to our quality 20 (Table 6). It can be seen that the number of trees is greater than that proposed for our quality 20, also that their diameter is less and that the production achieved is also lower.

French production tables for the Provence-Alpes-Costa Brava region (Couhert and Duplat, 1993) show higher yields in the first two qualities than those in Spain. In quality 16 (Table 6), which is a little better than the quality 20 defined for Spain, 21 m top height is reached at 80 years, a total volume of 462 $m^3 \cdot ha^{-1}$, 264 $m^3 \cdot ha^{-1}$ for the main stand before clearing and a maximum periodic increment at 45 years of 7.7 $m^3 \cdot ha^{-1} \cdot year^{-1}$. In all cases values are higher than those obtained in our quality 20.

There are a lot of studies of the silviculture and yield of *Pinus halepensis* which offer partial data on site quality, silvicultural practices and production. Ciancio (1986) for example proposes 40 year rotations for productive plantations in Italy (Table 6), recommending a thinning at 19 years leaving 1,111 trees $\cdot$ ha^{-1} with a diameter of 18 cm and another at 27 years, leaving 220-230 trees $\cdot$ ha^{-1} with a diameter of 30 cm. Finally, total production reached at 40 years is 440-480 $m^3 \cdot ha^{-1}$, 35 % of which has been removed in thinning.

Abbas (1983, 1986) makes a classification of five qualities, according to soil depth, and obtains the results shown in Table 7.

This mention of other published work may help the manager to compare our stands with those elsewhere, and to decide on a more informed basis to what extent the data provided in these and other studies in this area can be used to improve the silviculture of the species, or to complement the information in the tables here presented.

Table 7

Growth and top height in function of site index defined by soil depth (Abbas, 1986)

	SITE INDEX				
	I	II	III	IV	V
Mean depth soil (cm)	81-100	41-80	41-60	21-40	0-20
Mean increment ($m^3 \cdot ha^{-1} \cdot year^{-1}$)	5	4	3	1,5	1
Top height (m) at 75 years	20	18	16	13	10

CONCLUSIONS

As mentioned at the beginning of this report on growth and yield models are the best tool for designing a thinning regime, and are helpful in matters concerning forest inventorying and management. They are also a necessary tool in the resource planning essential to forest policy design. The yield models for variable silviculture of *Pinus halepensis* stands proposed in this study may be used in:

The classification of inventory units (stands) according to site quality.

The estimation of periodic increment in inventories for forest management.

The estimation of volumes with a fair degree of accuracy, if it is desired to do without inventories.

The adoption of a model of silviculture mainly concentrating on thinning regimes and the commercial classification of the products to be obtained.

Production forecasting for regional scale planning.

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RESUMEN

Modelos de crecimiento y producción de selvicultura para *Pinus halepensis* Mill.

A partir de los datos obtenidos de 72 parcelas instaladas en 1965, en masas repobladas de *Pinus halepensis,* inventariadas en 1965, 1970, 1975, 1980, 1988 y 1999, se han elaborado modelos de crecimiento y producción de selvicultura encontrada para cuatro calidades de estación. Las curvas de calidad se han definido por la altura dominante alcanzada a los 80 años de edad y se han ajustado por el modelo de Richards, resultando las siguientes curvas: calidad 20, calidad 17, calidad 14 y calidad 11. Posteriormente se han elaborado modelos de producción de selvicultura variable incluyendo dos regímenes de claras, simulados a través de la variación del índice de

Hart-Becking, para las calidades 20 y 17, que son las que presenta un mayor interés productivo. Para las calidades 14 y 11 se representan tablas con un único régimen moderado de claras, como corresponde a su mayor interés protector y su menor interés productivo.

PALABRAS CLAVE: *Pinus halepensis*
Calidad de estación
Modelos de producción y crecimiento
Tablas de producción
Selvicultura

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