Agroforestry Systems **43**: 151–167, 1999.

Growth of widely spaced trees. A case study from young agroforestry plantations in France

P. BALANDIER[1, *] and C. DUPRAZ[2]
[1]*CEMAGREF, Division Forêt et Agroforesterie, 24 avenue des Landais, BP 50085, F-63172 Aubière Cedex, France*; [2]*INRA, Lepse, 2 place P.-Viala, F-34060 Montpellier, France*
*(*Author for correspondence: E-mail: philippe.balandier@cemagref.fr)*

Key words: bole quality, intercropping, silvoarable systems, silvopastoral systems, tree shelter

Abstract. Pessimistic forecasts often suggest that widely spaced trees enjoying free growth (no competition with other trees) will fail to provide high quality timber. This challenges the temperate agroforestry practice of planting widely spaced trees to produce high quality timber. We analyse tree growth data from recent temperate agroforestry plantations aged three to eight years, featuring low tree plantation densities (50 to 400 stems ha^{-1}), the association of trees with intercrops (silvoarable systems) or animals (silvopastoral systems), and the use of plastic shelter tubes to protect trees (1.2 to 2.5 m high) and avoid damage by cattle or sheep in pastures or facilitate maintenance in silvoarable systems. The plantations are located in climates ranging from Mediterranean, dry central temperate plains, cold and wet central uplands to mild oceanic areas. Some plantations included a forestry control (high density of plantation, no tree shelter, no intercropping nor grazing). Trees were evaluated for height and diameter growth and stem form (straightness and absence of knots). Trees in most agroforestry plots grew satisfactorily, often faster than in forestry control plots. In some experimental plots, average annual height increments as high as 1 m and diameter increments as high as 1.5 cm were observed. Few agroforestry plantations were unsuccessful, and the reasons for the failures are discussed: animal damage in silvopastoral plots, but also a wrong choice of tree species unsuitable for local soil and climate characteristics. From these early results we can formulate some guidelines for designing future agroforestry plantations in temperate climates, concerning tree density, use of tree shelters and care required for widely spaced trees.

Introduction

The motives for agroforestry practice in France are diverse and include many non-productive applications such as landscape design or improved natural resources management (Rapey, 1994; Dupraz, 1994b). Trees can be associated with intercrops (silvoarable systems) or with grazing animals (silvopastoral systems). In both cases, experimented schemes combine two different features: sustainability of the intercrop production throughout most of the tree life, and a high value of the timber crop (Dupraz, 1994a; Guitton, 1996). In such conditions, agroforestry schemes have been demonstrated as potentially more profitable in France than a combination of pure agricultural and forest plots (Dupraz et al., 1996). To ensure sustainability of the intercrop and reduce plantation costs, the initial tree density should be as low as possible, consistent with a final harvest of 50 to 80 mature trees. On the one hand, decreasing tree planting density reduces selection possibilities. Consequently, trees must grow as well as possible to produce enough straight knot-free boles 4 to 6 m tall from a low initial density. On the other hand, to ensure agricultural income sustainability, trees have to be planted as widely spaced as possible to minimise competition of the trees with the crops or sward. Any tree that will not end up in a marketable product is a loss of investment and wasted competition with the intercrop. Therefore, a crucial question is whether very widely spaced trees (50 to 400 stem ha^{-1}) in agroforestry plantations grow correctly.

For several decades, there has been a trend in France to reduce broad-leaved forestry plantation densities, from often 2,500 or more to about 600 stems ha^{-1}. This process has culminated in agroforestry plantations. Many reasons account for this trend: improvements of the genetic quality of the seedlings, difficulties in marketing thinning products, and increases in plantation costs, often as a consequence of the need to protect the seedlings against game (Guitton and Ginisty, 1993; Guitton, 1996). Decreasing tree planting density can, however, generate certain growth or stem form problems not observed with higher densities. Protection against wind or excessive temperatures is limited in plots of widely spaced trees. Wind can have a direct mechanical effect, depreciating tree form (Crave, 1990). Open field conditions may increase frost risks; they increase water transpiration needs of isolated trees (Friedrich and Dawson, 1984; Aussenac, 1986), aggravating the competitive impact of the intercrop or sward (Frochot and Levy, 1986; Frochot, 1990; Baldy et al., 1994). Spontaneous shrubby vegetation in forestry plantations provides a side shelter effect, resulting in an improved juvenile growth of trees (Collet and Frochot, 1992). Finally, unpruned widely spaced trees usually produce poor shapes with large vigorous low branches, and greater stem taper (Brazier, 1977). Forks resulting in a double stem are a major stem defect, and occur more frequently in low-density plantations (Dupre et al., 1986; Nicolini and Caraglio, 1995 in beech; Barthelemy et al., 1995 in walnut). Consequently, low plantation density schemes require more attention, and pruning the trees to achieve high value clear boles is essential.

In agroforestry stands in France, mostly fast growing broad-leaved trees (*Prunus avium* L., *Juglans* sp., *Acer pseudoplatanus* L., *Fraxinus excelsior* L., *Sorbus* sp.,) producing high value timber with a veneer end-use have been planted. Most of the plantations are on private farms, where farmers grow their usual crops between the trees, with minimum disturbance of their farming system. Agroforestry stands have been planted since 1988 in different parts of France under ranging climates; Mediterranean (Dupraz and Lagacherie, 1990), dry central temperate plains, wet central uplands and cold oceanic areas (Rapey, 1994; Guitton et al., 1995). In silvopastoral plots, the trees are usually protected by a round plastic tube, 0.1 m wide, 1.2 to 2.5 m high (Tubex™), against cattle or sheep. In silvoarable plots, they may also be protected by tree shelters to facilitate maintenance. The use of tree shelters is controversial, because it can induce poor tree growth (Dupraz et al., 1993; Gill and Eason, 1994; Sibbald and Agnew, 1995).

Results concerning detailed tree form and pruning schemes in these young agroforestry plots aged three to eight years were presented in a recent paper (Balandier, 1997). We report here the first results obtained from the same plots concerning survival rate, external bole quality (straightness and absence of knots) and early height and diameter growth of the trees.

Materials and methods

Description and management of agroforestry stands

In 1996, the French agroforestry pool comprised 243 ha of plantations in 58 locations established from 1989 to 1996. Main tree species are *Acer pseudoplatanus* L., *Castanea sativa* Miller, *Fraxinus excelsior* L., *Juglans* spp., *Liriodendron tulipifera* L., *Paulownia* spp., *Populus* spp., *Prunus avium* L., *Pyrus communis* L., *Quercus* spp. and *Sorbus* spp. Experimental plots are distributed throughout a large part of the country, in different climates; cold with high rainfall, cool with moderate rainfall, oceanic, and mediterranean. Both silvopastoral (i.e., trees in pasture with grazing animals, generally cattle or sheep) and silvoarable systems (i.e., trees with intercrops) are being tested. 60% of the experimental plots are silvopastoral systems while 40% are intercropped.

Agroforestry tree plantation and management schemes have been designed with some common features (Guitton et al., 1990; Dupraz and Lagacherie, 1990; Rapey, 1994; Auclair et al., 1997) including low tree density (from 50 to 400 stems ha^{-1}) in square or rectangular patterns; round plastic shelter tubes (Tubex™) to protect the trees (0.1 m wide and 1.2 m tall in association with crops, 1.8 m with sheep and 2.5 m with cattle); strong stakes supporting the tree shelter; spot weeding within a radius of 0.6 m around the tree for the first three to five years; pruning the tree regularly every year to obtain a straight cylindrical bole 4 to 6 m tall with no branches after 10 to 15 years. The tree shelter is removed for pruning of the stem as soon as the tree canopy emerges, and is then placed back on the tree. It is definitively removed only once stem growth has split it open.

In some locations, forestry controls were set up simultaneously on the same plot of land using the same plant material. These forestry control plots were designed following the local guidelines for forestry planting, with higher plantation densities (from 600 to 1,400 stems ha^{-1}), simple rabbit guards instead of tree shelters, and no intercrop nor grazing. They were weeded within a radius of 0.6 m around the tree for three to five years.

Tree measurements

In most of the locations, all the trees have been measured for height and diameter growth every year in autumn ever since they were planted. Diameter at breast height could not be recorded where tall tree shelters prevented access to the tree stem. Therefore, the basal stem diameter (at 5 cm above the soil) was recorded. Damage to trees such as death, drying of branches, broken stems and damage from animals or machinery were recorded at the same time. At some locations, an assessment of the external bole quality (straightness and absence of knots) ranking from C (too many deformations, no future) to A (perfect straightness) was made. Damage to trees and bole quality assessement are not the same measurements; a tree undamaged (no broken stem or drying branches, etc.) can however have one or several deformations of the main stem and be classed C.

Data analysis

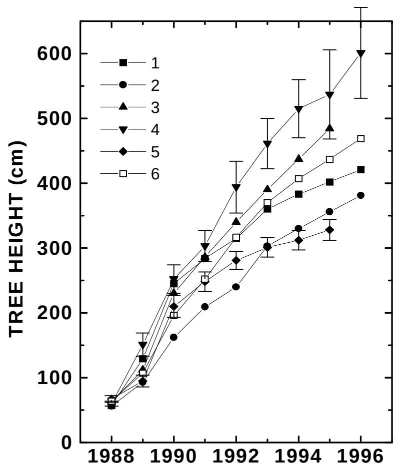
At each location, a block design would have been too awkward to manage by the farmer, so the treatments (agroforestry versus forestry, or tree species 1 versus tree species 2) were not strictly replicated. This lack of replication was compensated for by the large number of locations, the large size of the subplots, and by a statistical analysis using individual trees as pseudoreplications, as suggested by Pearce (1976). For each treatment (location, agroforestry or forestry scheme, tree species), the mean and confidence interval for the mean ($P = 0.05$) were calculated whenever at least 20 trees were available. Most data series followed a normal distribution. We approximated a normal distribution for the confidence interval calculation of some data series with a small number of replications. Student's t test was used to identify significant differences between growth means calculated on all trees ($P = 0.05$). The percentage of damaged trees was calculated each year for each treatment (location, agroforestry or forestry scheme, tree species). Bole quality assessment has been made when trees were eight year old. For a given location and species, there was no significant correlation between tree vigour and the occurrence of damage. Therefore height and diameter growth data have been analysed taking into account only the undamaged trees, resulting in an unbiased evaluation of treatment results.

Results

Height growth

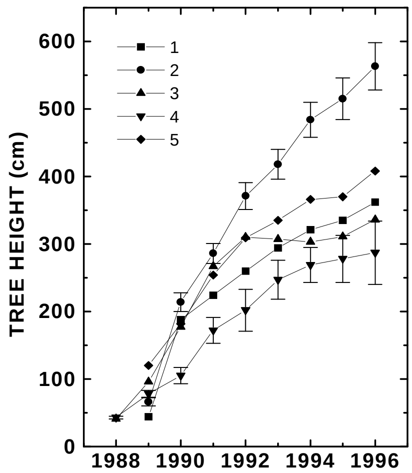
Eight years after plantation, the trees in agroforestry plots were 2.5 to 6 m tall, depending on species and local conditions (Figure 1). Poor growth was recorded at locations with very harsh conditions: high elevation with wind

a. *Acer pseudoplatanus* at 6 locations in Auvergne



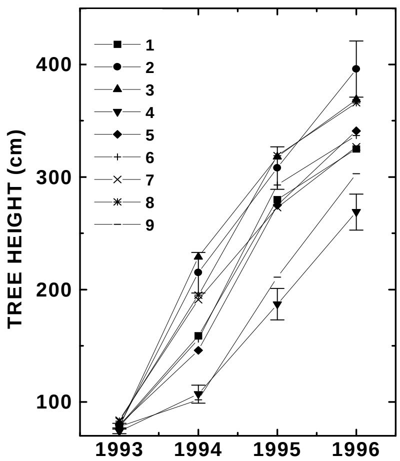
Locations: Berzet (1); Côtes (2); Gervais (3); Lamartine (4); Laqueuille (5); Orcival (6)

b. *Prunus avium* at 5 locations in Languedoc



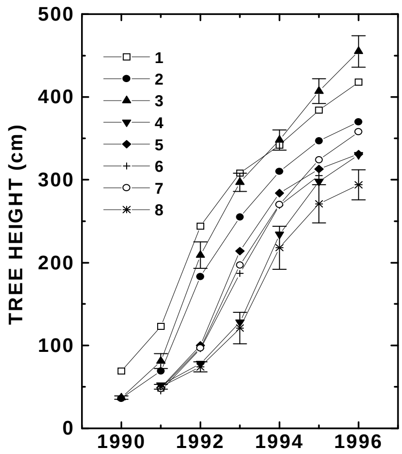
Locations: Campagne (1), Valmanya (2), Portes (3), Notre-Dame de Londres (4), Pomy (5).

c. *Fraxinus excelsior* at 9 locations in Pas-de-Calais



Locations: Becue. (1); Coqu. (2); Ducrocq. (3); Dumont (4); Duval (5); François (6); Hecq. (7); Leduc (8); Potez (9)

d. *Quercus rubra* in 8 different plots in the Ostabat estate, Pays-Basque



All plots at 100 trees/ha except (1) at 50 trees/ha

Trees were planted in March 1989 (a), March 1989 and 1990 (b), March 1994 (c) and March 1991 and 1992 (d). Trees were protected by tree shelters 1.8 m to 2.5 m tall. The confidence interval of the mean is drawn for the best and worst locations ($P = 0.5$).

Figure 1. Height growth of a) *Acer pseudoplatanus*, b) *Prunus avium*, c) *Fraxinus excelsior* and d) *Quercus rubra* in agroforestry plots (100 to 200 trees ha^{-1}) at different locations in Auvergne, Languedoc, Pays Basque and Pas-de-Calais, France.

and snow, strong wind, poor level of nutrients or low level of water availability. However, average height increments above 50 cm year^{-1} were often recorded (Table 1). On some high fertility locations the trees reached an average height of 6 m in eight years, with the tallest trees above 8 m.

Diameter growth

Basal stem diameters of the trees in agroforestry plots after eight growing seasons ranged from 2.5 to 9 cm according to species and location conditions (Figure 2). In most plantations, 0.8 to 1 cm year^{-1} annual basal diameter increments were observed, with 1.5 cm year^{-1} at some high fertility locations (Table 1). Recently, we observed a decrease in height increments concomitant with an increase in diameter increments, resulting in a steady increase in the tree stability. The height/diameter ratio (H/D) is often used to quantify tree stability, although it is generally applied to older trees. In our case, for most species, eight-year-old trees had reached H/D values below 100 (Figure 3). For mature trees, these values generally indicate a good stability.

Tree growth in agroforestry versus forestry control

In forestry plantations, the early height growth was always very slow (Figure 4 and Table 2). Fast growth was observed after a time lag that could be as long as three years (Table 2). These results indicate that trees in forest controls can soon catch up with agroforestry trees. Stem diameter growth data display a different pattern. Larger diameter increments were often observed in agroforestry plots in the last three or four years, whereas trees in the two systems exhibited similar growth during the first years (Figure 2). In contrast with the high H/D values of agroforestry trees during the first years, forest trees displayed H/D values below 90 (Figure 3). However, in some fast growing stands, agroforestry trees now display H/D ratios lower than forestry control trees competing with a vigorous shrubby stratum (Figure 3 c).

Tree death, injury and bole quality

The percentage of tree survival was generally high (> 80% in most cases) and no differences were observed between forestry controls and agroforestry plantations. High death rates were only observed where the tree species was unsuitable for the local soil or climate conditions.

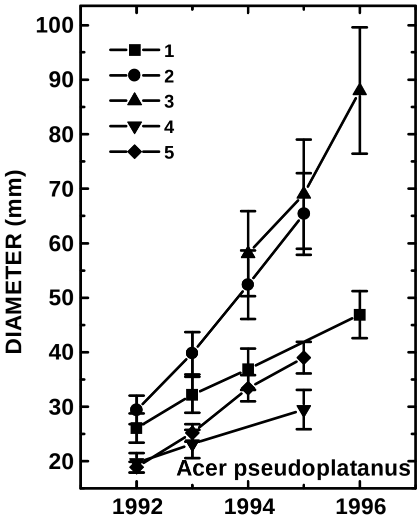
The percentage of trees injured by abiotic stresses (frost, water stress, stems broken by wind) or by animals was sometimes high (Table 1).

At high elevation this may have resulted from unfavourable climatic conditions such as strong winds, frost and snow or rime in winter. The use of tall tree shelters (from 1.8 to 2.5 m) to protect trees against cattle resulted in temporarily fragile slender stems. The trees were consequently very sensitive to wind and snow resulting at some locations in few trees with high quality

Table 1. Average height and basal stem diameter growth rates after emergence out of the tree shelters of undamaged trees in agroforestry stands established at different locations in France.

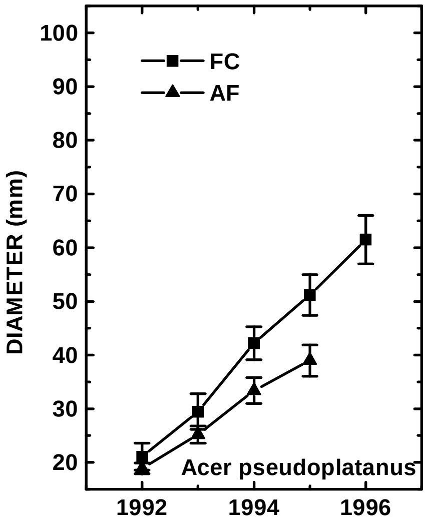
Location	Elevation (m)	Annual rainfall (mm)	Mean annual temperature (°C)	Soil available water content (mm)	Year of establishment	Tree species	Density of plantation (trees.ha^{-1})	Undamaged trees (%)	Growing seasons above tree shelters	Mean height increment (cm.year^{-1})	Mean diameter increment (mm.year^{-1})
Berzet	870	774	7.7	30	1989	*Fraxinus excelsior*	100	21	6	32	7.2
						Acer pseudoplatanus	100	25	6	29	5.2
Brioude	480	615	10.5	40	1990	*Juglans nigra*	50, 100	84	5	23	7.5
						Juglans regia × *nigra*	100	100	5	30	9.7
Campagne	450	700	12.6	50	1990	*Prunus avium*	400	60	4	45	6.3
Côtes	880	774	7.7	40	1989	*Fraxinus excelsior*	100	21	5	52	n.a.
				100		*Acer pseudoplatanus*	100	5	4	35	n.a.
Lamartine	810	774	7.7	110	1989	*Prunus avium*	200	71	6	56	12.2
						Acer pseudoplatanus	100	46	6	58	15.6
Laqueuille	1250	1223	6.7	70	1989	*Acer pseudoplatanus*	100	27	4	20	3.3
Montoldre	280	767	11.3	40	1990	*Prunus avium*	310	54	5	42	7.9
Orcival	1070	1130	6.6	95	1989	*Prunus avium*	100	67	5	56	12.8
						Fraxinus excelsior	100	66	5	52	8.4
Ostabat	180	1266	13.4	80	1991	*Quercus rubra*	200	75	4	61	11.4
						Acer pseudoplatanus	100	46	4	34	n.a.
Portes	350	1440	12.4	50	1989	*Quercus rubra*	400	75	5	33	3.4
						Alnus cordata	400	60	5	50	9.4
						Tilia tomentosa	400	70	5	30	4.7
						Pyrus communis	400	75	5	37	3.3
St Gervais	700	851	9.0	40	1989	*Prunus avium*	50, 100, 200	59	5	57	7.2
				120		*Acer pseudoplatanus*	100	39	5	51	12.7
				90		*Fraxinus excelsior*	100	69	6	47	14.3

a. Agroforestry plantations in Auvergne

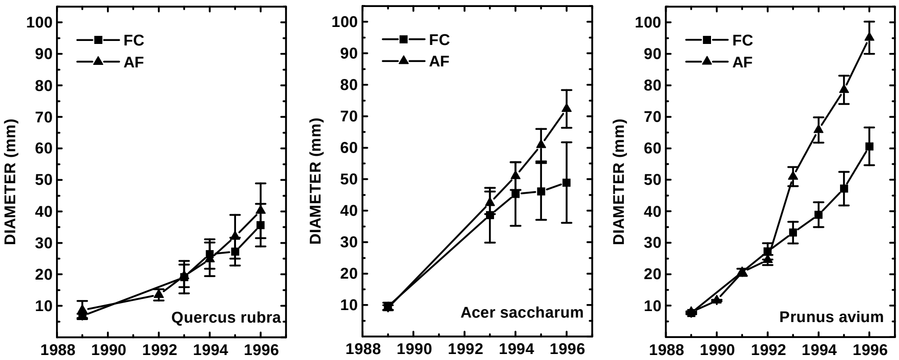


Locations : Berzet (1); Gervais(2); Lamartine (3); Laqueuille (4); Orcival (5)

b. Agroforestry versus forestry at Orcival



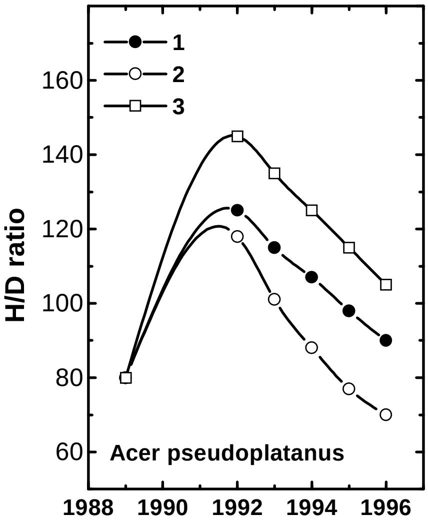
c. Agroforestry versus forestry at Valmanya (Languedoc-Roussillon)



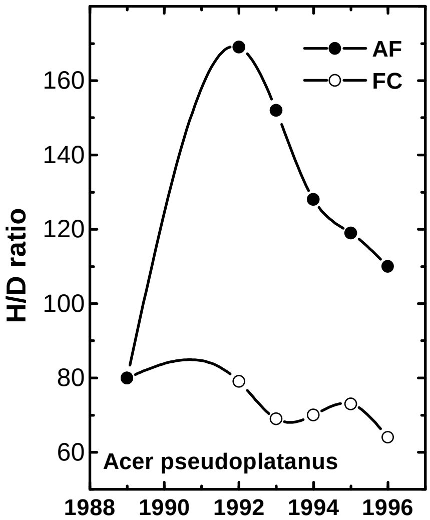
Trees were planted in March 1989 (a and b) and March 1990 (c) and protected by tree shelters. Trees in forestry controls (FC) were planted at the same time at 1,333 (b) or 1,100 (c) trees/ha with no protection by shelters. The vertical bars stand for the confidence interval of the mean (P = 0.05).

Figure 2. Basal stem diameter growth of *Acer pseudoplatanus*, *Quercus rubra*, *Acer saccharum* and *Prunus avium* in agroforestry plantations (AF) and forestry plantations (FC) at different locations in Auvergne and Languedoc, France.

a. Agroforestry plantations in Auvergne

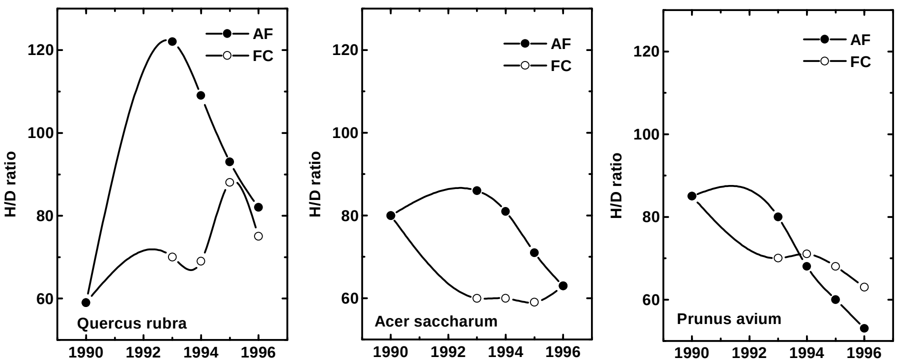


b. Agroforestry versus forestry at Orcival



Locations : Berzet (1); Gervais (2); Laqueuille (3)

c. Agroforestry versus forestry at Valmanya (Languedoc-Roussillon)



Same caption as Figure 2. Experimental points joined by a spline curve.

Figure 3. Height (H) to diameter (D) ratios (H/D) of *Acer pseudoplatanus*, *Quercus rubra*, *Acer saccharum* and *Prunus avium* in agroforestry (AF) and forestry plantations (FC) at different locations in Auvergne and Languedoc, France.

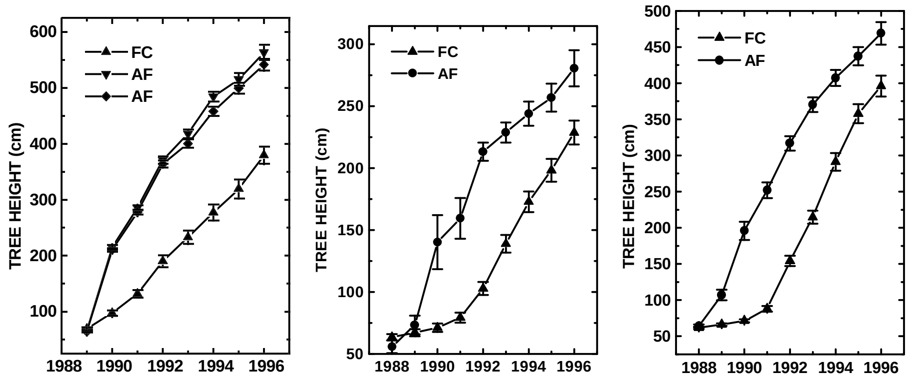
Table 2. Comparison of growth and stand parameters of trees in agroforestry plantations (AF) and forestry controls (FC) at different locations in France.

Location	Eleva-tion (m)	Year established	Tree Species	Density (trees ha^{-1})		Undamaged trees (%)		Height increment (cm year^{-1})			Basal stem diameter increment (mm year^{-1})	
				AF	FC	AF	FC	AF	FC[1]		AF	FC
									SG	FG		FG
Côtes	880	1989	*Prunus avium*	100	625	13	28	48	27* (3)	50 (5)	na	7.7
Orcival	1070	1989	*Acer pseudoplatanus*	200	1333	52	31	48	9* (3)	62 (5)	6.6	10.1*
Valmanya	980	1990	*Prunus avium*	400	1110	88	71	71	31* (2)	49* (5)	13.8	7.7*
			Acer saccharum	400	1110	96	60	54	30* (2)	34* (5)	9.0	5.7*
			Quercus rubra	400	1110	80	82	41	11* (3)	46 (4)	4.5	4.3
			Sorbus torminalis	400	1110	90	45	40	25* (3)	44 (4)	2.6	4.3
Pomy	570	1990	*Prunus avium*	400	1110	73	48	47	23* (2)	28* (5)	6.7	3.6*
			Acer platanoides	400	1110	73	50	39	7* (2)	12* (5)	4.0	1.5*
Notre-Dame	175	1989	*Juglans nigra*	400	400	60	90	32	5* (3)	38 (5)	5.2	6.1

[1] For the forest control plots, the growth increment was separately calculated for the first years with a slow growing pattern (SG; duration in years in brackets) and the following years with a faster growth (FG; duration in years in brackets).
Significant growth difference ($P = 0.05$) between the slow growing pattern of FC and AF, and the fast growing pattern of FC and AF, are indicated by an asterisk.

a. *Prunus avium* | b. *Juglans nigra* | c. *Acer pseudoplatanus*

high fertility location Valmanya, Languedoc-Roussillon | low fertility location Notre-Dame de Londres, Languedoc-Roussillon | medium fertility location Orcival, Auvergne



Trees were planted in March 1990 (a) and March 1989 (b and c).
The vertical bars stand for the confidence interval of the mean (P = 0.05).

Figure 4. Comparison of height growth of trees in forestry (FC) and agroforestry (AF) plantations at three locations in Languedoc-Roussillon and Auvergne, France.

boles remaining (Table 3 – Berzet, Orcival). The site of Berzet is an extreme case of this trend. Where the climatic and soil conditions were less constraining (low elevation, adequate protection against wind, high soil water availability) and the species were well chosen, most trees had a straight knot-free bole of high external quality (Table 3 – Pomy).

In silvopastoral plots, animals can also cause appreciable damage to the trees. In most experiments, sheep usually caused no damage to the trees although there were some exceptions (Table 3 – Berzet). In contrast, cattle damage was severe at some but not all locations (Table 3 – Aurillac).

Discussion

The fate of widely spaced forest trees in agroforestry plantations was uncertain when this research programme was launched (Savill and Spilsbury, 1991). The lack of neighbouring trees or of a shrubby vegetation stratum providing side protection to the young seedlings, and the detrimental competition of the intercrops were the most cited reasons for expecting failures (Frochot and Levy, 1986; Frochot, 1990). Eight years on, these pessimistic forecasts have not been borne out; the growth of widely spaced forest trees in agroforestry plantations has proved very satisfactory. The growth rates observed

Table 3. Assessment of the bole quality of wide-spaced forest trees and explanations for defects on tree boles in sheep and cattle silvopastoral experiments at four locations in Languedoc and Auvergne, France.

Location and animals	Pomy Sheep		Berzet Sheep		Orcival Cattle			Aurillac Cattle
Tree species	*Prunus avium*	*Acer platanoides*	*Acer pseudo-platanus*	*Fraxinus excelsior*	*Prunus avium*	*Acer pseudo-platanus*	*Fraxinus excelsior*	*Fraxinus excelsior*
Tree mortality (%)	4	13	21	0	10	14	5	14
Tree height at age 8 (m)	5.2	3.8	4.2	4.4	5.9	4.7	5.4	4.6
Pruned bole height at age 8 (m)	2.2	2.0	2.1	1.9	2.4	1.6	2.2	1.9
Expected pruned bole height (m)	4.0	4.0	3.0	3.0	6.0	4.0	4.0	6.0
Bole quality assessment at age 8								
No defects (%)	77	85	0	2	37	7	2	22
Some defects still rectifiable (%)	18	15	0	0	22	10	0	17
Many defects; no expected value (%)	5	0	100	98	41	83	98	61
Explanations for defects on tree boles								
Sheep or cattle damage	no		moderate		moderate			heavy
Growth defects	no	no	yes (wind)		yes (wind and snow conditions)			no
Plantation density required for obtaining a 80 trees ha^{-1} stand of perfect trees at age 8	104	94	no	no	216	no	no	360
High forestry densities probably more advisable			yes	yes		yes	yes	

in agroforestry plots (height increments over 50 cm year^{-1}) match those generally observed in forestry plantations in France for the same tree species: 30 to 80 cm year^{-1} for the first 10 years of growth for *Quercus rubra* (Le Goff et al., 1993), 30 to 50 cm for *Juglans regia* and 30 to 70 cm for *Juglans nigra*, 80 cm for *Fraxinus excelsior* (Balandier and Marquier, 1998). Failure to grow in both forestry controls and agroforestry plantations was clearly related to the choice of tree species unsuited to local conditions.

After five years, the height growth of agroforestry trees slowed while their diameter growth increased. This has been reported for wide spaced trees and isolated trees (Cabanettes et al., 1999). After five years, forestry plots were often invaded by a competitive shrubby stratum, causing the trees to grow faster in height, usually interpreted as a result of competition for light (Aussenac, 1986; Hubert, 1992). Thus the patterns observed in agroforestry and forestry stands are opposite. While in some cases the forestry trees were catching up with the agroforestry trees, in most cases the gap in size was still widening. However, comparing trees with the same age but different heights may be unsound; when tree growth at the same tree height is compared, agroforestry trees still grow faster than forest trees in most cases and particularly when diameter increments are compared.

Comparison of growth results observed in forestry control and agroforestry plantations is also not easy as it cannot be easily designed as a factorial experiment (Dupraz, 1999). In forestry plantations, tree growth depends mostly on the suitability of the tree species for the location and on the effectiveness of tending operations. In agroforestry plantations, the interactions with the intercrop (and/or animals) confuse the issue, besides the impact of the tree shelters. Weeds and shrubs (in forestry plots) and crops or swards (in agroforestry plots) compete for water and nutrients, which obviously strongly influences the growth pattern (Anderson and Sinclair, 1993; De Montard et al., 1999). Tree shelters enhance height growth and depress diameter growth while the tree canopy grows inside the shelter, during one to three growing seasons, according to the height of the shelter and the tree vigour (Dupraz, 1997a). In forestry plots competitive shrubs and neighbouring trees may in certain cases have a similar impact on tree growth (Frochot and Levy, 1986). A prolonged negative effect has been observed during the two years following tree emergence outside of the tree shelter, and may be related to the rooting pattern of sheltered trees (Dupraz, 1997a). New ventilated tree shelters are expected to minimise this depressive impact of tree shelters on tree growth (Dupraz, 1997b). Whenever possible, agroforestry experiments should include a forestry control with tree shelters and an agroforestry plantation (for tree density) without intercrops.

Stem form defects appeared to be the most important constraint to overcome and can result from many causes (animals in silvopastoral systems, tree shelter, birds breaking top shoots, human vandalism, climatic accidents, and architectural defects such as forks) which can act alone or together. In the harshest upland conditions (elevation, frost, strong wind) tree stem form is particularly poor as most of the trees have been bent or broken by the wind. In such low site index and windy conditions, wide spaced trees will not produce enough quality boles to make the plantation profitable, and a high forestry density may be more advisable than an agroforestry plantation (Table 3). The use of tall tree shelters leading to slender stems has worsened the wind effect. New ventilated tubes which improve tree diameter growth would probably improve tree resistance against wind and lead to better results. Sheep rarely caused tree damage in our experiments whereas cattle were more aggressive. However, there is no general rule. Animal damage often results from the conjunction of several factors acting together: shortage of available forage on the plot (Bird et al., 1995), overstocking, poor parasites control leading to rubbing, mistakes in flock management, tall tree shelters (1.8 to 2.5 m) leading to slender stems bent by the wind and caught by the animals (Balandier et al., 1997). With aggressive cattle, a barbed wire spiral around the tree shelter and the stakes has proved efficient in keeping animals away from trees (Balandier et al., 1997).

As a consequence, in harsh upland conditions or when animal management is difficult, a conservative planting density of 200 stems.ha^{-1} or more may be safe (Table 3). An alternative scheme would be to plant at low densities and replace dead or poorly growing trees until the target final density is obtained. In the worst locations, only high forestry densities or tree protection against wind would be advisable.

In the best locations (protected from wind and frost, with a good soil fertility and available water content), we observed that with careful pruning, up to 70% of straight and knot-free boles were obtained, indicating that a planting density of 100 stems ha^{-1} would be acceptable to secure a final stand of 50 to 80 trees ha^{-1} of quality trees (Table 3). However, these figures implicitly assume that no new hazards will affect the trees until the full bole is achieved, in another five or 10 years time. This may be optimistic, but it was observed that the percentage of high quality boles has been stable for the last years, suggesting that the critical time for stem formation is now over.

Conclusion

A pessimistic prognosis suggested that young trees enjoying free growth (no competition with other trees) would have a poor growth and fail to provide high quality timber. However, based on growth data after five to eight years, wide spaced broad-leaved trees in agroforestry plots in temperate and mediterranean conditions have so far grown very satisfactorily compared with the same species in neighbouring forestry stands. Some failures were recorded, but they affected both forestry and agroforestry plantations, and were the result of a wrong choice of species for the prevailing local conditions.

In carefully pruned agroforestry plantations, a large proportion of straight knot-free boles were obtained in most stands, although five more years will often be required to achieve the 4–6 m tall size aimed for. The number of high quality stems obtained per hectare depended on various factors. At most high fertility locations (and in particular those protected from wind and frost, and with a good available soil water content), failure to achieve a high quality bole was very rare, suggesting that low initial density of plantation would be acceptable (i.e., less than 200 stems.ha^{-1}). At low fertility locations (and particularly those at high elevation, exposed to wind and frost or those with a low available soil water content), more failure was observed, and a higher planting density would be required to obtain a full final density of about 80 mature trees ha^{-1}.

Acknowledgements

The authors thank G. Agrech, G. Bretières, M. Dauzat, A. Marquier and B. Suard for their technical contributions in the field and B. Cabannes, J.L. Guitton, M. Lagacherie and H. Rapey for planting and follow-up of the experimental plots. They also thank D. Auclair for his help in improving this paper. The development of the agroforestry network was supported by grants from the European Community (EC), contract AIR-CT92-0134, the Auvergne and Languedoc-Roussillon Regions, the Pyrénées-Atlantiques district, the Ostabat township and the Boulonnais producers’ association.

References

Anderson LS and Sinclair FL (1993) Ecological interactions in agroforestry systems. Agroforestry Abstracts 6(2): 57–91

Auclair D, Etienne M, Bergez JE, Dupraz C, Rapey H and Willis R (1997) An interdisciplinary approach for modelling silvopastoral systems under temperate conditions. In: Proceedings of a workshop ‘L’agroforesterie pour un développement rural durable’, Inra-Cirad editors, Montpellier, France, 1997/06/23–29, 385–389

Aussenac G (1986) La maîtrise du microclimat en plantation. Rev For Fr 38(3): 285–292

Balandier P (1997) A method to evaluate needs and efficiency of formative pruning of fast-growing broad-leaved trees and results of an annual pruning. Can J For Res 27: 809–816

Balandier P, Rapey H and Guitton JL (1997) Mise en valeur et développement durable des zones de moyennes montagnes par l’agroforesterie: l’association arbre – herbe – animal. In: ‘proceedings of the XI world Forestry Congress’, Antalya, Turkey, 1997/10/13–22, vol. 1, A2, 6 pp

Balandier P and Marquier A (1998) Vers une remise en question des avantages d’une plantation frêne – aulne. Rev For Fr 50(3): 231–243

Baldy C, Dupraz C and Schilizzi S (1994) Vers de nouvelles agroforesteries en climats tempérés et méditerranéens. Cahiers Agricultures 2: 375–386

Barthélémy D, Sabatier S and Pascal O (1995) Le développement architectural du noyer commun *Juglans regia* L. (Juglandaceae). Forêt-Entreprise 103: 61–68

Bird PR, Kellas JD, Kearney GA and Cumming KN (1995) Animal production under a series of Pinus radiata-pasture agroforestry systems in South-West Victoria, Australia. Australian J Agr Res 46: 1299–1310

Brazier JD (1977) The effect of forest practices on the quality of the harvested crop. Forestry 50(1): 49–66
Cabanettes A, Auclair D and Imam W (1999) Diameter and height growth curves for widely-spaced trees in European agroforestry. Agrofor Syst 43: 169–181
Collet C and Frochot H (1992) Effet d'un abri latéral artificiel sur le développement de jeunes merisiers (*Prunus avium* L.) installés en pépinière. Rev For Fr 44: 85–90
Crave MF (1990) L'effet du vent sur les noyers. Forêt-Entreprise 66: 13–17
De Montard FX, Rapey H, Delpy R and Massey P (1999) Competition for light, water and nitrogen in an association of hazel and cocksfoot. Agrofor Syst 43: 135–150
Dupraz C (1994a) Prospects for easing land tenure conflicts with agroforestry in Mediterranean France: a research approach for intercropped timber orchards. Agrofor Syst 25: 181–192
Dupraz C (1994b) Le chêne et le blé: l'agroforesterie peut-elle intéresser les exploitations européennes de grandes cultures? Rev For Fr 46 (special issue): 84–95
Dupraz C (1997a) Abris-serres: ce qu'en pensent les arbres . . . . Rev For Fr 49(5): 417–432
Dupraz C (1997b) Les protections de plants à effet de serre: amélioration de leur efficacité par aération optimisée et luminosité accrue. Rev For Fr 6: 519–530
Dupraz C (1999) Adequate design of control treatments in long term agroforestry experiments with multiple objectives. Agrofor Syst 43: 35–48
Dupraz C and Lagacherie M (1990) Culture de feuillus à bois précieux en vergers pâturés sur des terres agricoles du Languedoc-Roussillon: le réseau expérimental APPEL. Forêt Méditerranéenne 12(4): 447–457
Dupraz C, Guitton JL, Rapey H, Bergez JE and De Montard FX (1993) Broad-Leaved Tree Plantations On Pastures: The Treeshelter Issue. In: Proceedings of the 4th International Symposium on Windbreaks and Agroforestry, Viborg, Denmark, 106–111
Dupraz C, Lagacherie M, Liagre F and Cabannes B (1996) Des systèmes agroforestiers pour le Languedoc-Roussillon. Impact sur les exploitations agricoles et aspects environnementaux. Inra-Lepse editor, Montpellier, France, 418 pp
Dupre S, Thiebaut B and Teissier du Cros E (1986) Morphologie et architecture des jeunes hêtres (*Fagus sylvatica* L.). Influence du milieu, variabilité génétique. Ann Sci For 43(1): 85–102
Friedrich JM and Dawson JO (1984) Soil nitrogen concentration and Juglans nigra growth in mixed plots with nitrogen-fixing Alnus, Eleagnus, Lespedeza, and Robinia species. Can J For Res 14: 864–868
Frochot H (1990) Compétition et relation de voisinage dans les jeunes peuplements forestiers. In: Proceedings of the '14e Conférence du Columa', Versailles, France, 861–870
Frochot H and Lévy G (1986) Facteurs du milieu et optimisation de la croissance initiale en plantations de feuillus. Rev For Fr 38(3): 301–306
Gill EK and Eason WR (1994) Tree protection options in silvopastoral agroforestry. Agroforestry Forum 5(2): 32–33
Guitton JL (1996) Tree culture for a valuable wood production. SkogFork, The forestry Research Institute of Sweden, Uppasala, Sweden, report 2: 82–90
Guitton JL, Bretière G and Saar S (1990) Culture d'arbres à bois précieux en prairies pâturées en moyenne montagne humide. Etudes du Cemagref, Série Forêt n° 4, Antony, France, 199 pp
Guitton JL and Ginisty C (1993) Les plantations à grands espacements. Informations Techniques du Cemagref 90(1), 8 pp
Guitton JL, Balandier P and Rapey H (1995) Mise au point d'une agroforesterie moderne: avancement du programme de recherche/développement en Auvergne. Forêts de France 382: 10–14
Hubert M (1992) La végétation d'accompagnement: un auxiliaire sylvicole à surveiller de près. Forêt-Entreprise 82(2): 39–47
Le Goff N, Colin-Belgrand M and Muller G (1993) Croissance et productivité du chêne rouge dans le Nord-Est de la France. In: 'Le chêne rouge d'Amérique', INRA editions, Paris, France, 172–176
Nicolini E and Caraglio Y (1995) L'influence de divers caractères architecturaux sur l'apparition de la fourche chez *Fagus sylvatica* L. (Fagaceae) en fonction de l'absence ou

de la présence d'un couvert. In: Proceedings of 'Architecture des arbres fruitiers et forestiers', 1993/11/23–25, Montpellier, France, Colloque collection 74: 273–287
Pearce SC (1976) Field experimentation with fruit trees and other perennial plants. Commonwealth Agric. Bur., Farnham Royal, Bucks, England
Rapey H (1994) Les vergers à bois précieux en prairie pâturée: Objectifs, principes et références. Rev For Fr 46: 61–71
Savill PS and Spilsbury MJ (1991) Growing oaks at closer spacing. Forestry 64(4): 373–384
Sibbald A and Agnew B (1995) Silvopastoral National Network Experiment – 1994 Annual Report. Agroforestry Forum 6(1): 5–8