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Development and application of bio-economic modelling to compare silvoarable, arable and forestry systems in three European countries

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Abstract

Silvoarable agroforestry could promote use of trees on farms in Europe, but its likely effect on production, farm profitability, and environmental services is poorly understood. Hence, from 2001 to 2005, the Silvoarable Agroforestry for Europe project developed a systematic process to evaluate the biophysical and economic performance of arable, forestry, and silvoarable systems in Spain, France, and the Netherlands. A biophysical model called "Yield-SAFE" was developed to predict long-term yields for the different systems and local statistics and expert opinion were used to derive their revenue, costs, and pre- and post-2005 grant regimes. These data were then used in an economic model called "FarmSAFE" to predict plot- and farm-scale profitability. Land equivalent ratios were greater than one, showing Yield-SAFE predicted that growing trees and crops in silvoarable systems was more productive than growing them separately. Pre-2005 grants in Spain and the Netherlands penalised silvoarable systems, but post-2005 grants were more equitable. In France, walnut and poplar silvoarable systems were consistently the most profitable system under both grant regimes. In Spain, holm oak and stone pine silvoarable systems were the least profitable system under pre-2005 grants, but only marginally less profitable than arable systems under post-2005 grants. In the Netherlands, low timber values and the opportunity cost of losing arable land for slurry manure application made silvoarable and forestry systems uncompetitive with arable systems under both grant regimes.

Introduction

Agroforestry is a form of multi-cropping, involving at least one woody-perennial species, and ecological and economic interactions between the components. Agroforestry systems can be described by their components (crops, animals and trees) and their spatial (dispersed or zoned) and temporal (coincident to sequential) arrangement (Nair 1985, Sinclair 1999). Silvoarable agroforestry is defined as the practice of growing an arable crop between spatially zoned trees (Dupraz and Newman, 1997, Burgess et al., 2004b)

Most research on agroforestry systems has evaluated their biophysical performance despite the observation that it is often socio-economic constraints that limit their adoption (Graves et al., 2004, Mercer et al., 1998). In practice, because of biophysical and socio-economic interactions (Dyack et al., 1999), there is a need to consider both of these together. However, complete empirical data for entire tree rotations are rare and computer simulations therefore provide a means of systematically undertaking biophysical and economic analyses of silvoarable systems in the absence of such data.

Various biophysical and economic models have been developed for monocultures of arable and forestry systems, but relatively few have been developed for silvoarable agroforestry (Graves et al., 2005). Current bio-economic models of silvoarable agroforestry range from detailed biophysical models with limited economic analysis to economic models that use biophysical data from an external source (Graves et al., 2005). Bio-economic modelling has been used to examine profitability (Thomas 1991, Willis et al. 1993, Thomas and Willis, 1997; Burgess et al. 2000) and feasibility (Dupraz et al., 1995) of silvoarable agroforestry in Europe. Profitability is usually assessed at a plot- (one-hectare) scale and performance is compared with that in competing systems, such as arable and forestry systems. Feasibility is usually determined at a farm-scale to view how silvoarable agroforestry affects cash-flow and resource use. This paper describes the integrated use of a biophysical and an economic model, at both a plot- (one-hectare) and farm-scale, to determine the profitability of silvoarable systems in comparison with arable and forestry sytems. In particular, it describes the effect of grants on the profitability of silvoarable systems relative to that of arable and forestry systems. The study focuses on three countries, Spain, France, and the Netherlands, selected because of their differing climates, tree and crop species, and grant regimes.

Method

In order to determine the profitability of arable, forestry, and silvoarable systems, a method comprising five steps was used. These included: 1) identifying and characterising potential sites for the uptake of silvoarable agroforestry, 2) defining potential arable, forestry and silvoarable systems for those sites, 3) using a bio-physical model to determine yields for those systems, 4) defining the revenue, costs and grant regimes associated with each site, and 5) using an economic model to determine the financial effects at a plot- and farm-scale.

Identification and characterisation of landscape test sites

Since a major objective was to determine if silvoarable agroforestry could provide a profitable alternative land use in areas dominated by arable cropping, potential sites were limited to areas where there was arable land, as specified by the Pan-European Land Cover Monitoring (PELCOM) project (Mücher *et al.* 2000). The sites were also restricted to those areas belonging to the three dominant environmental classes in each country (or one in the case of the Netherlands), as described by Mücher *et al.* (2003) in a statistical analysis of climate and topography. Within these constraints, three landscape test sites, measuring 4 km x 4 km, from each environmental class, were randomly selected using a geographical information systems, to give nine, nine, and three landscape test sites in Spain, France and the Netherlands respectively. Two sites in France were later discarded for lack of associated data, giving 19 sites altogether (Table 1).

Table 1. Summary of the latitude, longitude, altitude, mean air temperature, annual solar radiation receipt and annual rainfall at each site

Country and region	Site name	Latitude	Longitude	Altitude (m)	Mean temp (°C)	Solar radiation (MJ m^{-2})	Annual rainfall (mm)
Spain							
Andalucia	Alcala la real	37.36N	3.88W	1000	15.3	5490	355
Castilla La Mancha	Torrijos	39.89N	4.39W	500	15.5	5560	348
	Ocaña	39.94N	3.44W	700	14.7	5780	316
	Almonacid de Zorita	40.23N	2.61W	900	12.6	6610	404
Castilla y Leon	Cardenosa El Espinar	40.78N	4.53W	1000	12.0	5700	404
	Fontiveros	40.86N	5.00W	900	12.0	6170	393
	Olmedo	41.28N	4.80W	750	12.5	5480	410
	St Maria del Campo	42.11N	3.91W	800	9.1	5630	530
	St Maria del Paramo	42.44N	5.69W	800	10.2	6600	519
France							
Poitou Charentes	Champdeniers	46.41N	0.02E	200	11.0	4740	648
Centre	Chateauroux	46.92N	1.65E	150	11.0	4750	587
	Fussy	47.18N	2.47E	200	10.6	4800	626
	Sancerre	47.30N	2.72E	400	10.7	4590	724
Franche Comté	Champlitte	47.64N	5.58E	300	8.5	4940	773
	Dampierre	47.61N	5.82E	300	10.0	5090	1072
	Vitrey	47.81N	5.78E	400	9.5	4900	1084
The Netherlands							
	Bentelo	52.22N	6.67E	0	8.8	3690	729
	Balkbrug	52.57N	6.34E	0	8.9	4830	818
	Scherpenzeel	52.57N	6.34E	0	9.0	3710	801

Note: for the rest of the paper, Alcala la Real, Almonacid de Zorita, Cardenosa el Espinar, St Maria del Campo and St Maris del Paramo are referred to as Alcala, Almonacid, Cardenosa, Campo and Paramo respectively.

To provide input data for the biophysical model, daily mean values of air temperature, total short-wave radiation, and rainfall were generated for each landscape test site using CLIGEN 5.2 (United States Department of Agriculture, 2005) with reference values from the nearest weather station (Global Data Systems, 2005). The annual values for

mean air temperature and total radiation were highest in Spain (9.1-15.5^{o}C and 5480-6600 MJ m^{-2}) and lowest in the Netherlands (8.8-9.0^{o}C and 3690-4830 MJ m^{-2}) (Table 1). Mean annual rainfall was lowest in Spain (320-530 mm) and highest in France (590-1080 mm). In Spain, much of the rainfall occurred in winter, with minimal rainfall in summer. In France, seasonality of rainfall, although greatly reduced, was still evident, while in the Netherlands, rainfall was generally consistent throughout the year.

Soil depth and texture were defined for each landscape test site, and using a classification of hydraulic properties of European soils (Wösten et al. 1999), available soil water content was described using van Genuchten's equation (1980). Further data layers for elevation and land cover were developed, and the effect of topography on relative radiation was calculated from digital elevation models in the Digitales Gelände-Modell (DiGeM©) (Conrad, 2002). Field visits were also made to each site to confirm existing interpretation, improve existing data, and provide missing data.

To provide a qualitative description of the arable land in each landscape test site, between one and four "land units" were defined, by excluding non-arable land and then using a cluster analysis of available soil water content and relative solar radiation receipt on the remaining area (Table 2). In total, there were 42 land units.

Definition of tree and crop species and management

The land units defined for each landscape test site were ranked according to their quality, and expert opinion was used to determine the most suitable tree species and crop rotation for each land unit. In Spain, the trees selected were holm oak (*Quercus ilex*) and stone pine (*Pinus pinea*), in France, wild cherry (*Prunus avium*), walnut (*Juglans* spp.), and poplar (*Populus* spp.) and in the Netherlands, walnut and poplar. In Spain, arable systems were based on wheat, sunflower, and fallow. In France, arable systems at Champdeniers, Chateauroux, Fussy, and Sancerre were based on wheat and sunflower and, in the Franche Comté region (Champlitte, Fussy and Vitrey) on wheat, oilseed and grain maize. In the Netherlands, wheat and forage maize were assumed for the arable systems. The silvoarable systems integrated the forestry tree species and arable crop species and rotation for each land unit.

The management of the arable systems reflected local practice. Management of the forestry systems was also based on local practice. In Spain, planting densities, thinning and pruning for oak were derived from Pulido et al., (2003), and for stone pine, from Yagüe (1995) and Montero and Cañella (2000). In France, management for forestry systems was developed using the Institut pour le Développement Forestier (1997), Souleres (1992), Boulet-Gercourt (1997) and the Centre Régional de la Propriété Forestière (1997). In the Netherlands, the receipt of grants was conditional on an appropriate planting density (Ministerie van Landbouw, Natuur en Voedselkwaliteit, 2004). It was assumed that each tree species was planted in year 1 and holm oak, stone pine, wild cherry and walnut were "harvested" to provide revenue in year 60. For poplar, a rotation of 20 years was assumed with re-planting in years 21 and 41. Management of the silvoarable systems combined the management of the arable and forestry systems, or use expert judgement as appropriate.

Table 2. The total utilised agricultural area for each hypothetical farm and description of the 42 different land units, and the selected tree and crop species

Country	Land unit	Area (ha)	Radiation (%)	Soil texture	Soil depth (cm)	Tree	Crop rotation
Spain	Alcala 1	58	97	M	140	Oak	w/w/f
	Alcala 2	15	86	M	50	Oak	w/w/f
	Torrijos 1	10	101	M	140	Oak	w/f
	Torrijos 2	56	100	M	140	Oak	w/w/f
	Ocaña	66	100	M	140	Oak	w/w/f
	Almonacid 1	59	97	M	140	Oak	w/f
	Almonacid 2	7	83	F	140	Oak	s/s/s/s/s/w/f
	Cardenosa 1	23	93	M	140	Oak	w/w/w/f
	Cardenosa 2	35	101	F	140	Oak	w/w/w/f
	Fontiveros 1	49	99	C	140	Oak	w/w/w/w/f
	Fontiveros 2	9	98	C	140	Pine	w/w/w/w/f
	Olmedo 1	5	100	C	140	Pine	w/s/f
	Olmedo 2	34	100	M	140	Oak	w/s/f
	Olmedo 3	18	99	C	140	Oak	w/s/f
	Campo 1	44	99	C	140	Pine	w/w/w/f
	Campo 2	14	99	M	140	Oak	w/w/w/w/w/f
	Paramo 1	4	100	M	140	Oak	w/w/w/s/f
	Paramo 2	34	100	M	140	Oak	w/w/w/s/f
	Paramo 3	21	101	M	140	Oak	w/w/w/s/f
France	Champdeniers 1	67	100	F	80	Cherry	w/w/s/w/o/s
	Champdeniers 2	27	100	M	120	Walnut	w/w/s/w/o/s
	Chateauroux 1	32	102	F	80	Walnut	w/w/o/w/o/s
	Chateauroux 3	86	102	M	120	Walnut	w/w/o
	Chateauroux 2	23	102	F	40	Cherry	w/w/o/w/o/s
	Chateauroux 4	11	100	F	40	Cherry	w/w/o/w/o/s
	Fussy 1	10	101	F	40	Cherry	w/o
	Fussy 2	43	103	M	80	Poplar	w/w/o
	Fussy 3	27	102	F	120	Cherry	w/o
	Sancerre 1	37	103	F	40	Cherry	o/w/s/w/w/w/o
	Sancerre 3	44	101	Vf	120	Cherry	o/w/s/w/w/w/o
	Sancerre 4	7	100	C	80	Cherry	o/w/s/w
	Sancerre 2	10	102	Vf	140	Poplar	o/w/s/w/w/w/o
	Champlitte 1	68	103	M	140	Cherry	w/w/o
	Champlitte 2	62	103	M-f	35	Walnut	w/w/w/w/w/gm
	Dampierre 1	64	98	M	140	Cherry	w/w/gm
	Dampierre 2	43	97	F	35	Cherry	w/w/w/gm
	Dampierre 3	23	95	Mf	60	Poplar	w/gm
	Vitrey 1	46	103	M	60	Cherry	w/w/o
	Vitrey 2	74	103	Mf	60	Poplar	w/w/gm
Netherlands	Bentelo 1	40	100	C	140	Walnut	w/w/fm
	Balkbrugg 1	40	100	C	140	Poplar	fm
	Scherpenzeel 1	10	100	C	140	Poplar	fm

Note: Soil texture: C: coarse; M: Medium; M-f: Medium-fine, F: Fine; V-f: Very fine
Crop type: w: wheat; f: fallow; o: oilseed; s: sunflower; gm: grain maize; fm: forage maize

Biophysical modelling

The tree and crop yields for the selected arable, forestry, and silvoarable systems were modelled using YieldSAFE (van der Werf et al., 2006). A default set of parameters for the "potential" yield of each tree and crop species (Van Ittersum and Rabbinge, 1997) was developed, assuming no water limitation on growth (Burgess et al. 2004a). These parameters were then used to determine water limited "reference" yields for the forestry and arable systems by adjusting three parameters (harvest index, water use efficiency and a management factor) within acceptable boundaries, so that predicted Yield-SAFE yields matched reference yields. Local crop and tree management, and radiation, rainfall, temperature, and soil depth data for each landscape test site were used as inputs for Yield-SAFE. Dry wood densities assumed for timber ranged from 410 kg m^{-3} for poplar to 900 kg m^{-3} for oak; intermediate values of 570 to 608 kg m^{-3} were used for walnut, stone pine, and wild cherry. The reference yields for each crop and tree species were determined from national statistics and expert opinion, during workshops in each country.

Using the parameter set developed for reference yields and soils at each landscape test site, tree and crop yields for each land unit were predicted for monoculture forestry and arable systems and two silvoarable systems of 50 or 113 trees ha^{-1}. From the biophysical yields, it was possible to estimate a land equivalent ratio (*LER*) for each system. Land equivalent ratios were initially defined for mixed cropping systems (Mead and Willey, 1980) and have been adapted for agroforestry systems (Ong 1996, Dupraz, 1998). The land equivalent ratio is "the ratio of the area under sole cropping to the area under the agroforestry system, at the same level of management that gives an equal amount of yield" (Ong, 1996) and is expressed as:

$$LER = \frac{Tree\ silvoarable\ yield}{Tree\ monoculture\ yield} + \frac{Crop\ silvoarable\ yield}{Crop\ monoculture\ yield} \qquad \textbf{Equation 1}$$

Where more than one crop occurred in the rotation, a weighted ratio for each crop was used, depending on its proportion in the rotation.

Definition of revenue, costs and grants

Financial data on the revenue and costs associated with arable, forestry, and silvoarable systems were collected on electronic templates for each landscape test site, using local and national statistics, and expert opinion (Graves, 2005). For the crop component of the silvoarable system, the variable and assignable fixed costs were applied according to the proportion of the arable area in the system. It was also assumed that cropping would only continue if the intercrop net margin (calculated on a five year moving average to remove the effect of yield variation) was profitable, after which it was assumed the intercrop area would be fallowed.

The financial data for forestry and the tree component of the silvoarable system comprised the revenue from timber and subsidies, and the costs of woodland establishment and management. The revenue from timber was calculated using relationships between the standing value of a cubic metre of timber and the timber volume for each species in each country. The costs associated with the forestry system and the tree component of the silvoarable systems were based on various sources.

A particular focus of this study was the effect of grants, and three regimes were examined: a zero grant regime, a pre-2005 grant regime, associated with direct area payments, and a post-2005 grant regime associated with the single farm payment scheme. The pre- and post-2005 grant regimes for arable, forestry, and silvoarable systems was established from local, national, and European documents (European Commission, 2004), and expert opinion. However, since the post-2005 grant regime for silvoarable agroforestry was unclear, two extreme scenarios were developed. In scenario 1, the single farm payment was assumed for the percentage of cropped area in the system, without tree payments. In scenario 2, the single farm payment was assumed for the whole system, with a planting grant to cover 50% of the tree costs in the first four years of the tree rotation.

Plot-scale economic modelling

The predicted annual yields of trees and crops were used as inputs for a plot- and farm-scale cost-benefit economic model called "FarmSAFE" (Graves et al., 2005).
In arable systems, profitability is typically compared on an annual and per unit area basis by adding the revenue generated (R) to the variable costs associated with generating that revenue (V) to give a gross margin (Gross margin = $R - V$) (Nix, 1999; Ministry of Agriculture, Fisheries and Food, 1983). However because other costs such as labour and machinery, sometimes termed "assignable fixed costs" (A), are modifiable over a long time period, it is common practice to compare arable, forestry, and silvoarable systems on the basis of their net margin (Net margin = $R - V - A$) (Willis et al. 1993; Burgess et al. 2000, Graves et al., 2005). As the benefits and costs associated with tree-based systems occur over many years, discounted cost benefit analysis was used to define the present value of future costs and benefits from the arable, forestry, and silvoarable systems, using the approach first defined by Faustmann (1849). The net present value (NPV; units: € ha^{-1}) was expressed as:

$$NPV = \sum_{t=0}^{t=T} \frac{(R_t - V_t - A_t)}{(1+i)^t} \qquad \textbf{Equation 2}$$

Where: NPV was the net present value of the arable, forestry, or silvoarable enterprise (€ ha^{-1}), R_t was the revenue from the enterprise (including subsidies) in year t (€ ha^{-1}), V_t was the variable costs in year t (€ ha^{-1}), A_t was the assignable fixed costs in year t (€ ha^{-1}), T was the time horizon (years), and i was the discount rate (discount rate = 4%).

In order to compare systems with different rotation lengths, an infinite net present value was calculated. This was the net present value defined over an infinite rotation, in which each replication had a rotation of n years. The infinite net present value ($iNPV$; units: € ha^{-1}) was defined as:

$$iNPV = NPV \frac{(1+i)^n}{(1+i)^n - 1} \qquad \textbf{Equation 3}$$

The infinite net present value was also expressed as an equivalent annual value (EAV) using the following formula:

$$EAV = iNPV \times i \qquad \textbf{Equation 4}$$

The zero, pre- and post-2005 grant regimes were examined in terms of their effect on the economic performance of the arable, forestry, and the silvoarable systems (113 trees ha^{-1} only) using the equivalent annual value (discount rate = 4%).

Farm-scale modelling

In order to assess the feasibility of the selected silvoarable systems at a farm-scale, hypothetical cereal farms in each landscape test site were determined from regional data. In Spain, this was obtained from the Farm Accountancy Data Network (FADN) (European Commission, 2005), in the Netherlands, from the Agricultural Economics Research Institute (2005), and in France, from the Réseau d'observation des systèmes d'exploitation (ROSACE) (Assemblée Permanente des Chambres d'Agriculture, 2005). Where hypothetical cereal farms could not be determined from the available data, hypothetical farms were defined using the most commonly occurring farm type in the region. For each landscape test site, the area of each land unit relative to the total area of the land units was used to represent the proportion of each land unit within the hypothetical farms.

The FarmSAFE model was used to determine the effect of up to four arable, four forestry, and four silvoarable systems on the financial resources of each farm. Economic feasibility at the farm-scale was determined using the infinite net present value of the farm ($iNPV_{farm}$; units: € $farm^{-1}$). This aggregated net present values of the different systems and the net present value of "farm fixed costs" (F_t: units: € $farm^{-1}$) over the same period of time, and was defined as:

$$iNPV_{farm} = \left(\sum_{l=1}^{l=4} \left(NPV_a a_a + NPV_f a_f + NPV_s a_s \right) - \sum_{t=0}^{t=T} \frac{F_t}{(1+i)^t} \right) \frac{(1+i)^n}{(1+i)^n - 1} \qquad \textbf{Equation 5}$$

Where: l was one of four possible land units, NPV_a, NPV_f, and NPV_s were the net present values (€ ha^{-1}) of arable, forestry and silvoarable enterprises in each unit l; a_a, a_f, and, a_s were the area (ha) of arable, forestry, and silvoarable systems in each unit l, F_t was the farm fixed cost in year t (€ $farm^{-1}$), T was the time horizon (years), i was the discount rate and n was the duration of the rotation (years).

The infinite net present value of the farm was used to evaluate the economic effect of planting 10% of the farm with forestry or silvoarable systems, in comparison with the arable status quo of the hypothetical farms at each landscape test site, under the pre- and post-2005 grant regimes.

Results

Yields in arable and forestry systems

In Spain, the reference timber volumes for oak and stone pine in year 60 were assumed to be 0.22-0.26 m^3 $tree^{-1}$, indicating relatively slow growth. In France, wild cherry (1.04-1.06 m^3 $tree^{-1}$) and walnut (1.04 m^3 $tree^{-1}$) yields in year 60 were relatively high, indicating relatively fast-growing trees. Poplar was the fastest growing tree with reference yields of 1.46-1.51 m^3 $tree^{-1}$ in year 20. In Spain, the reference yields for wheat were relatively low (1.62-3.71 t ha^{-1}) compared to those in France (6.5-8.0 t ha^{-1}) and the Netherlands (7.8 t ha^{-1}). Reference sunflower yields were also lower in Spain (0.60-1.09 t ha^{-1}) than in France (2.3-2.5 t ha^{-1}). Reference yields for oilseed (3.2-4.0 t ha^{-1}) and grain maize (7.5-8.0 t ha^{-1}) were assumed only for France and a reference yield for fodder maize (12 t ha^{-1}) assumed only for the Netherlands.

Crop yields developed using Yield-SAFE showed inter-annual variation around the reference values for each site, due to the inter-annual variation in temperature, rainfall, and solar radiation. Crop yields ranged from 0.2 t ha^{-1} for sunflower in Spain to 15.9 t ha^{-1} for maize in the Netherlands (Table 3). Although the greatest absolute variation in yield was associated with high yielding crops in the Netherlands and France, the relative variation in yields was greatest in Spain. For the forestry systems, the timber volume per tree ranged from 0.23 m^3 for holm oak after 60 years, to 1.59 m^3 for poplar after 20 years. Standard deviations showed that absolute yield variation was relatively high for wild cherry in France and poplar in the Netherlands; coefficients of variation showed that relative yield variation was relatively high for oak in Spain, wild cherry in France, and poplar in the Netherlands.

Table 3 Summary and description of yields for crops and trees in France, Spain and the Netherlands

Country	Arable crop	No of values	Mean (t ha^{-1})	Standard deviation (t ha^{-1})	Range (t ha^{-1})	Coefficient of variation (%)
Spain	Sunflower	120	0.8	0.4	0.2-1.7	52
	Wheat	697	2.5	1.0	0.6-5.8	40
France	Grain maize	61	6.3	1.2	2.9-9.8	20
	Oilseed	260	3.2	0.4	1.9-4.3	13
	Sunflower	106	1.7	0.4	0.7-2.6	26
	Wheat	613	5.5	1.5	0.9-10.5	27
Netherlands	Forage maize	80	11.5	1.7	8.0-15.9	15
	Wheat	20	7.9	1.2	5.9-11.1	16
	Tree species		(m^3 ha^{-1})	(m^3 ha^{-1})	(m^3 ha^{-1})	(%)
Spain	Oak (60)	16	0.33	0.050	0.23-0.43	15
	Pine (60)	3	0.25	0.005	0.25-0.26	2
France	Cherry (60)	12	0.88	0.151	0.71-1.15	17
	Poplar (60)	4	1.34	0.143	1.26-1.59	11
	Walnut (60)	4	1.01	0.008	1.00-1.02	1
Netherlands	Poplar (20)	2	1.28	0.215	1.06-1.49	17
	Walnut (60)	1	0.71	n/a	0.71	n/a

Note: values in brackets show length of rotation

For each crop, except wheat in Spain, there was a significant positive correlation between predicted annual crop yields and soil depth (Table 4). Predicted timber yields were also positively correlated with soil depth for cherry, poplar and oak (Table 4). However, this correlation was only significant (P=0.05) in the case of wild cherry.

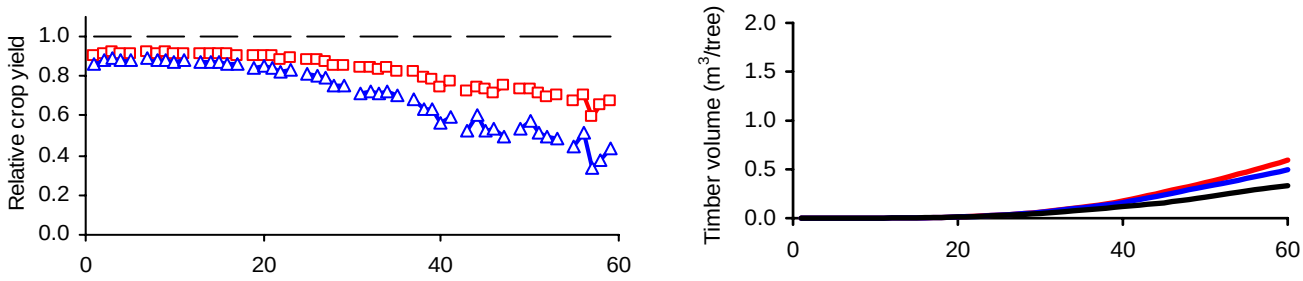
Table 4 Relationship between a) crop yield and b) timber volume and soil depth for selected crop and tree species in Spain and France

Country	Crop or tree species	No of pairs	Linear regression of crop yield (t ha^{-1}) or timber volume (m^3 ha^{-1}) against depth (*d; m*)	Correlation coefficient	Significant (P=0.05)
Spain	Wheat	697	2.34 (± 1.02) + 0.19 *d*	0.02	No
France	Wheat	613	3.69 (± 1.23) + 2.15 *d*	0.57	Yes
	Grain maize	61	4.90 (± 0.92) + 1.82 *d*	0.67	Yes
	Sunflower	106	1.06 (± 0.39) + 0.72 *d*	0.49	Yes
	Oilseed	260	2.95 (± 0.42) + 0.32 *d*	0.26	Yes
Spain	Oak	16	0.17 (± 0.04) + 0.12 *d*	0.53	No
France	Cherry	12	0.64 (± 0.10) + 0.29 *d*	0.75	Yes
	Walnut	4	1.02 (± 0.01) + 0.0028 *d*	-0.12	No
	Poplar	4	0.98 (± 0.04) + 0.42 *d*	0.97	No

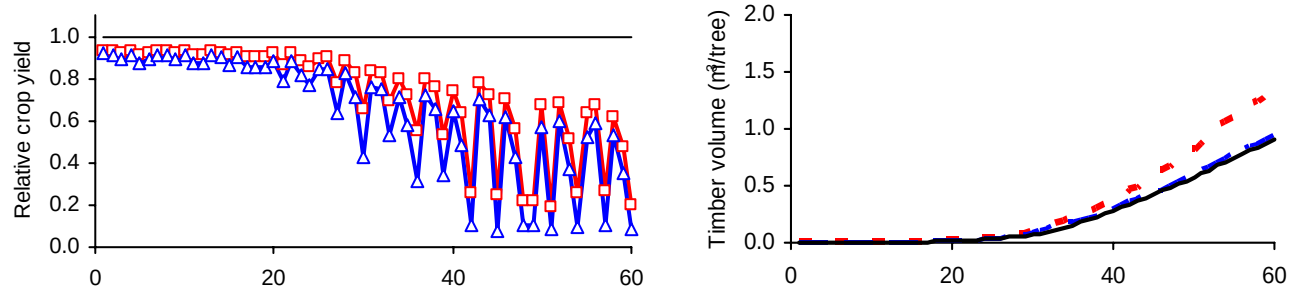
Yields in silvoarable systems

The biophysical outputs from Yield-SAFE for the silvoarable systems (50 and 113 trees ha^{-1}) showed a general decline in crop yields as the trees became larger and competed more effectively for light and water (Figure 1). Oak (Figure 1a) and stone pine (which showed similar growth over time to oak and is therefore not shown) grew slowly throughout the whole rotation. Hence, relatively high crop yields were sustained for most of the tree rotation. The initial rate of timber formation by wild cherry (Figure 1b) was slow compared with walnut (Figure 1c) and poplar (Figure 1d), and crop yield reduction in the walnut and poplar systems was predicted to occur earlier than in the wild cherry systems. As expected, crop yields and tree growth (on a per tree basis) were greater in 50 tree ha^{-1} systems than in 113 tree ha^{-1} systems (Figure 1).

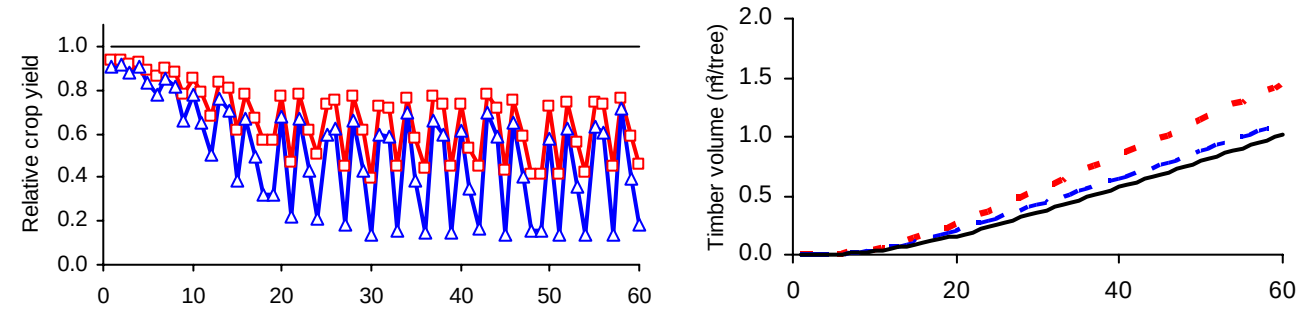
a) Land unit 2, St Maria del Campo, Spain (oak; wheat/wheat/wheat/wheat/wheat/fallow)



b) Land unit 1, Champdeniers, France (wild cherry; wheat/wheat/s/wheat/oilseed/sunflower)



c) Land unit 2, Champdeniers, France (walnut; wheat/wheat/s/wheat/oilseed/sunflower)



d) Land unit 1, Sherpenzeel, the Netherlands (poplar; forage maize)

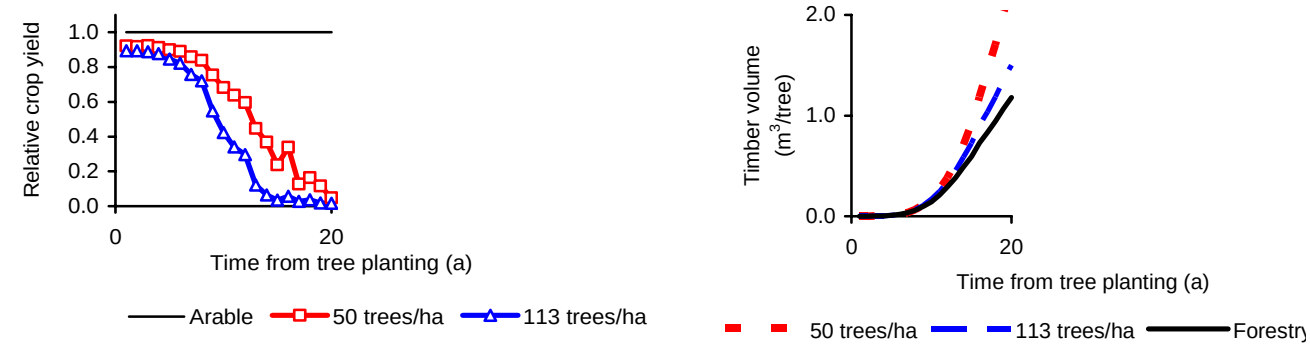


Figure 1 Prediction of relative crop yields and timber volumes over time for a) oak, b) wild cherry, c) walnut, and d) poplar silvoarable systems (50 and 113 trees ha^{-1}) on four different land units.

Over the whole length of the tree rotation, crop yields relative to those in arable systems were greatest in the 50 tree ha^{-1} systems and timber yields relative to those in forestry systems were greatest in the 113 tree ha^{-1} systems (Figure 2). During a full tree rotation, in both France and Spain, the relative yield obtained for autumn-planted wheat tended to be greater than that for spring-planted sunflower (Figure 3a and 3b). Similarly, under poplar in the Netherlands (Figure 3c), the relative yield obtained for wheat (autumn-planted) was greater than that for forage maize (spring-planted). Relative timber production also varied between species. At 113 trees ha^{-1} relative timber production was higher for walnut, wild cherry, and poplar (63-81%) then for oak and stone pine (34-37%) (Figures 2a); a similar pattern between the species was evident at 50 trees per ha^{-1}, but the relative yields (45-56% and 17-19% respectively) were lower (Figures 2b).

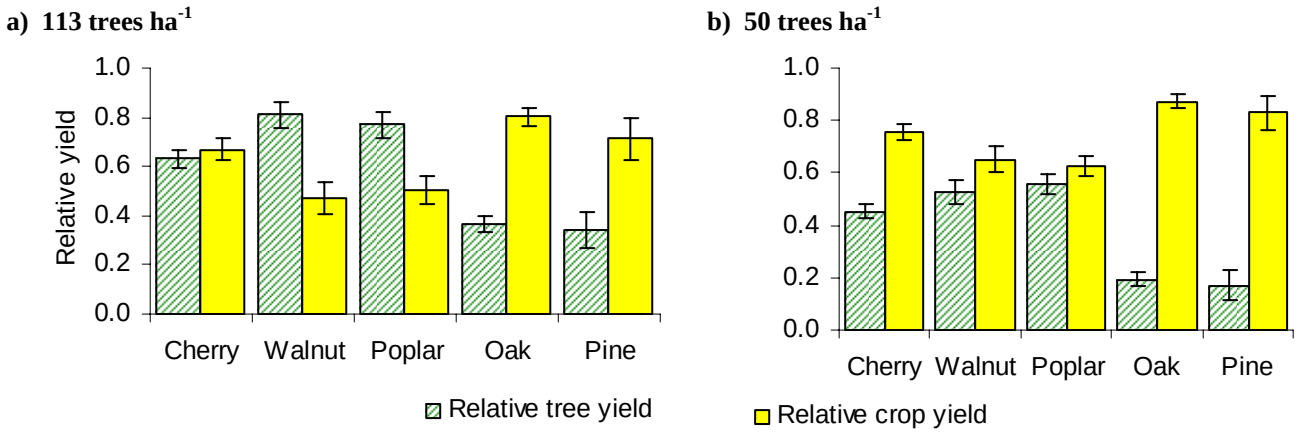


Figure 2 Tree and crop yields in cherry, walnut, poplar, oak, and pine silvoarable systems at a) 113 trees ha^{-1} and b) 50 trees ha^{-1}, relative to monoculture yields (error bars show confidence intervals for mean values).

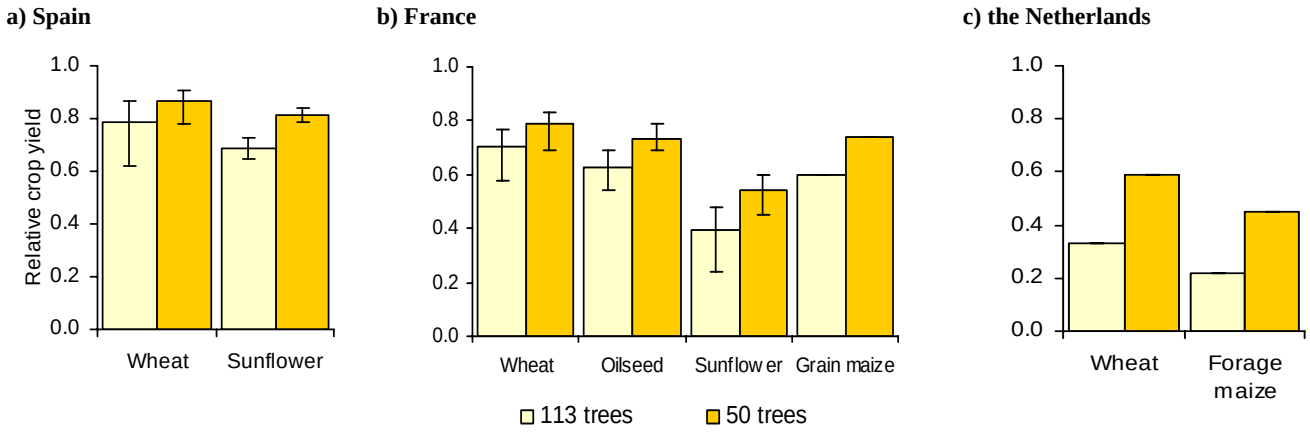
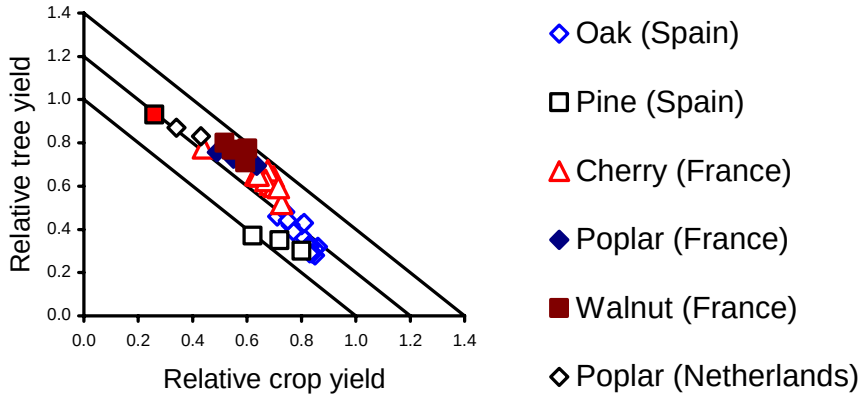


Figure 3 Crop yields in silvoarable systems of 113 and 50 trees ha^{-1} in a) Spain and b) France under all tree species, and c) the Netherlands under poplar, relative to monoculture yields (error bars show the maximum and minimum values in each group)

Land equivalent ratios

With a few exceptions, and including thinnings for timber and a full rotation for crop yields, the predicted land equivalent ratios of the silvoarable systems (Equation 1) at both 113 and 50 trees ha^{-1} were between 1 and 1.4. Hence the Yield-SAFE model predicted that, under typical management, integrating crops and trees on the same area of land was more productive than growing them separately. The relationship between relative tree and crop yields suggested that the land equivalent ratio would form a convex arc, with maximum values obtained when the trees and crops had similar relative yields, and minimum values where either the tree or crop component was dominant (Figures 4a and b). At each landscape test site, the land equivalent ratio at 113 trees ha^{-1} (Figure 4a) was greater than that at 50 trees ha^{-1} (Figure 4b). At both tree densities, the highest land equivalent ratios were associated with poplar, walnut and cherry systems in France (Figure 4); the lowest land equivalent ratios were associated with oak and pine in Spain.

a) 113 trees per hectare



b) 50 trees per hectare

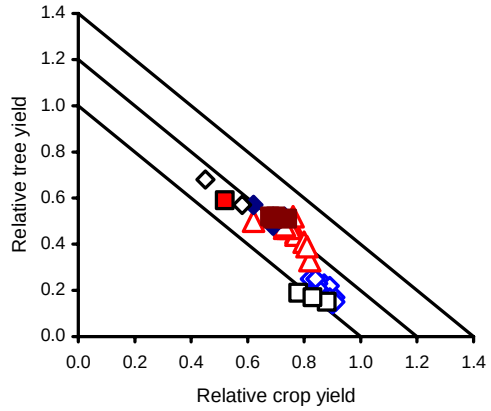


Figure 4 Relationship between relative crop yield and relative tree yield for the walnut and poplar (France and the Netherlands), cherry (France), and oak and pine silvoarable systems (Spain) at a) 113 trees ha^{-1} and b) 50 trees ha^{-1}.

Definition of revenue, costs and grants

The revenue and costs associated with the tree and crop systems are fully described by Graves (2005). However, for clarity some key values are described here.

Arable and silvoarable crop component finance

The values for arable crops ranged from 85 € t^{-1} for grain maize to 280 € t^{-1} for sunflower; the values for wheat grain ranged from 102 to 142 € t^{-1}. The variable costs tended to be lowest in Spain, at between 45 and 189 € ha^{-1}, and highest in the Netherlands, at between 457 and 479 € ha^{-1}. The assignable fixed costs, such as machinery and labour costs, followed a similar pattern, tending to be lowest in Spain and highest in the Netherlands.

Forestry and silvoarable tree component finance

In Spain, the values recorded for oak (17 € m^{-3}) and pine (8-19 € m^{-3}) were relatively low. By contrast, in France, the values recorded for walnut (40-1300 € m^{-3}), wild cherry (10-380 € m^{-3}), and poplar (7-55 € m^{-3}) were relatively high. In the Netherlands, the value recorded for walnut (18-41 € m^{-3}) was much lower than in France, but the value of poplar (19-97 € m^{-3}) was slightly higher.

The establishment costs of forestry systems were greatest in the Netherlands (3420 € ha^{-1} for walnut; 1940 € ha^{-1} for poplar) and lowest in Spain (770 € ha^{-1}) for oak systems at 400 trees ha^{-1}. The establishment costs for forestry systems of cherry (1510 € ha^{-1}), walnut (1633 € ha^{-1}), and poplar (1260 € ha^{-1}) in France and high density oak (1470 € ha^{-1}) and pine (1786 € ha^{-1}) in Spain were intermediate. The establishment cost of the tree component in the 113 tree ha^{-1} silvoarable systems ranged from 1200 € ha^{-1} for walnut in the Netherlands, to 233 € ha^{-1} for oak in Spain. Management costs after establishment were highest for the systems in France and the Netherlands, where control of undergrowth and pruning involved substantial costs. In addition, in the Netherlands, an annual opportunity cost of 408 € ha^{-1} was assumed for arable land converted to forest, because of the problem of finding land for slurry application; this cost was applied on a pro-rata basis to the tree-rows in the silvoarable system.

Grant regimes

Under the pre-2005 grant regime, the cash value (discount rate = 0%) of forestry payments was greatest in the Netherlands and lowest in France (Table 5). The arable area payments were marginally greater in the Netherlands than in France, but both were much greater than those for the chosen systems in Spain.

Table 5 The predicted value of government support (€ ha^{-1}), over a full tree-rotation (60 years for oak, pine walnut and cherry; 20 years for poplar), for forestry, arable and silvoarable systems in the pre-2005 grant regime, and the predicted change in that support in a post-2005 grant regime (scenario 1 and scenario 2)

Country, tree species and land unit		Pre-2005 government support				Predicted net change in support with the post-2005 grant regime			
		Rotation (a)	Forestry	Arable	Silvoarable	Forestry	Arable	Silvoarable scenario 1	Silvoarable scenario 2
Spain									
Oak	Alcala 1	60	6860	5170	2010	-2940	8030	10010	11410
	Alcala 2	60	6860	5170	2690	-2940	8030	9320	10730
	Torrijos 1	60	9380	3870	1410	-4190	210	820	1260
	Torrijos 2	60	9380	5170	1920	-4180	270	1790	2380
	Ocaña 1	60	9380	5170	1770	-4190	350	2120	2860
	Almonacid 1	60	9380	3870	1380	-4190	600	2010	2710
	Almonacid 2	60	9370	8770	4080	-4180	-1030	2980	3890
	Cardenosa 1	60	8860	5810	2900	-3380	-590	1850	2540
	Cardenosa 2	60	8860	5810	2670	-3390	-590	2080	2770
	Fontiveros 1	60	8850	6200	2940	-3380	950	3570	4430
	Olmedo 2	60	8860	5160	2260	-3390	600	2990	3720
	Olmedo 3	60	8860	6100	2520	-3380	-340	2720	3460
	Campo 2	60	8860	6460	2610	-3380	1990	4160	6060
	Paramo 1	60	8860	6760	3080	-3390	2500	5350	6400
	Paramo 2	60	8860	6760	3080	-3390	2500	5350	6400
	Paramo 3	60	8860	6760	3060	-3390	2500	5370	6420
Pine	Fontiveros 2	60	8000	6200	2060	-2960	950	4450	5340
	Olmedo 1	60	8010	6100	1780	-2970	-340	3470	4220
	Campo 1	60	8010	5810	1050	-2970	1790	2640	4260
France									
Cherry	Champdeniers 1	60	4440	21180	16130	0	0	-390	1560
	Fussy 3	60	3840	21090	19590	0	-30	-430	1870
	Sancerre 3	60	3840	20860	19380	0	-70	-460	1800
	Fussy 1	60	3840	21090	19590	0	-30	-420	1870
	Chateauroux 2	60	3840	21000	19510	0	-50	-440	1840
	Chateauroux 4	60	3840	21000	19510	0	-50	-440	1840
	Sancerre 4	60	3850	20940	19450	0	-150	-530	1740
	Sancerre 1	60	3840	20860	19380	0	-70	-460	1810
	Champlitte 1	60	0	20080	11880	0	-100	-60	2170
	Dampierre 1	60	0	21040	15320	0	-1300	-1550	870
	Vitrey 1	60	0	19840	14450	0	-60	-50	2760
	Dampierre 2	60	0	20940	12700	0	-1200	-730	860
Walnut	Champdeniers 2	60	4270	21180	16440	0	0	-700	1570
	Chateauroux 3	60	3670	20800	19630	0	150	-570	2030
	Chateauroux 1	60	3680	21000	19820	0	-50	-750	1840
	Champlitte 2	60	0	19880	3920	0	100	20	3450
Poplar	Sancerre 2	20	2720	6940	6850	0	-10	-540	610
	Fussy 2	20	2720	6960	6870	0	60	-480	680
	Dampierre 3	20	0	7080	3870	0	-500	-280	610
	Vitrey 2	20	0	6600	3610	0	-10	-10	880
Netherlands									
Walnut	Bentelo	60	11810	23000	5230	-1980	-1820	-410	2810
Poplar	Balkbrug	20	11810	8000	3640	-3310	0	0	1030
	Sherpenzeel	20	11810	8000	4370	-3640	0	0	1100

In Spain, support for silvoarable agroforestry was lower than for forestry and the arable systems, because of ineligibility for tree grants and reduction of the crop payments according to a canopy area based calculation. In France, in Poitou Charentes and Centre (Champdeniers, Fussy, Sancerre, and Chateauroux), arable payments were at least five-times the value of forestry payments; the value of silvoarable payments was marginally

less than that for arable systems. In Champlitte, Dampierre, and Vitrey in Franche Comté, there were no forestry payments. Support for walnut and poplar forestry in the Netherlands was identical, because both were assumed to be temporary, production-based systems. Since arable payments were dependent on the length of the tree rotation, they were greater for walnut (Bentelo) than for poplar (Balkbrug and Scherpenzeel). In each case, the support for silvoarable systems was less than for forestry and arable systems, as no payments were received for the tree component.

In the post-2005 grant regime, existing levels of payments for forestry applied where they were in accordance with the rural development strategy of the European Union (European Commission, 2004). There was therefore no change in France. However in Spain and the Netherlands, planting payments were changed to 50% of tree costs in the first four years and the compensation payments and maintenance grants were reduced to 500 € ha^{-1} a^{-1} with a maximum duration of 10 years, unless they were already below these levels. In general, arable and especially silvoarable payments were predicted to increase in Spain. The predicted value of the new single farm payment at Alcala, Paramo and Campo was greater than pre-2005 area payments, as the generous support for non-arable activities on the farms typical of these areas, was assumed to be re-allocated on an area basis. In France, there were only marginal changes for arable systems, due to modulation under the single farm payment. For silvoarable systems, scenario 1 was generally similar to the pre-2005 regime but marginal benefits were evident under scenario 2.

Plot-scale economic results

Profitability with no grants

The equivalent annual values of the forestry systems with oak and stone pine in Spain, poplar and walnut in the Netherlands, and cherry in France were negative (Table 6). Only walnut and poplar in France was profitable. The equivalent annual values of the arable system were positive at Alcala, Cardenosa, Fontiveros, Olmedo and Paramo in Spain, at Champdeniers, Chateauroux, Fussy and Sancerre in France, and at all sites in the Netherlands. By contrast the returns from arable systems were negative in Torrijos, Ocaña and Campo and at most sites in Franche Comté (i.e. at Dampierre and Vitrey) (Table 6). The equivalent annual value of the silvoarable systems in Spain were marginally below those for the arable system. By contrast, in France, values for the silvoarable systems with walnut, with poplar in Centre, and with wild cherry in Poitou Charentes and Franche Comté were higher than those for both arable cropping and forestry. In the Netherlands, the values for the silvoarable system with poplar were marginally greater than the arable system, but the value for the silvoarable system with walnut was negative (Table 6).

Table 6 Equivalent annual value (€ ha^{-1} a^{-1}) (discount rate of 4%) of the arable, forestry, and silvoarable (113 trees ha^{-1}) system in Spain, France and the Netherlands, a) without grants, b) under the pre-2005 grant regime, and c) the post-2005 grant regime (scenario 1 and 2).

Country, tree species and land unit		a) No grants			b) Pre-2005			c) Post-2005			
		Forestry	Crop	Silvoarable	Forest	Crop	Silvoarable	Forest	Crop	Silvoarable scenario 1	Silvoarable scenario 2
Spain											
Oak	Alcala 1	-57	99	67	184	191	125	97	333	279	310
	Alcala 2	-50	47	30	190	139	97	103	281	242	272
	Torrijos 1	-36	-13	-5	290	56	23	166	59	36	51
	Torrijos 2	-37	-39	-9	289	53	11	166	57	35	52
	Ocaña 1	-37	-32	-11	289	59	29	166	66	42	50
	Almonacid 1	-40	-20	-13	286	48	-56	163	59	36	52
	Almonacid 2	-46	18	0	280	172	108	157	154	124	145
	Cardenosa 1	-59	113	98	245	215	172	156	205	182	200
	Cardenosa 2	-55	115	98	248	218	169	160	207	181	199
	Fontiveros 1	-56	100	72	248	210	162	159	226	200	221
	Olmedo 2	-54	58	38	250	149	105	161	160	136	154
	Olmedo 3	-55	8	-9	248	115	62	160	109	85	103
	Campo 2	-57	-54	-25	247	61	8	158	96	61	84
	Paramo 1	-51	196	176	253	315	258	164	360	325	349
	Paramo 2	-51	196	176	253	315	258	164	360	325	349
	Paramo 3	-50	195	175	253	314	257	165	359	324	348
Pine	Fontiveros 2	-80	100	57	190	210	129	118	227	181	203
	Olmedo 1	-80	7	-15	190	115	34	118	109	71	90
	Campo 1	-80	-73	-34	190	30	-9	118	61	13	34
France											
Cherry	Champdeniers 1	-111	14	68	63	380	353	63	381	336	384
	Chateauroux 2	-152	35	40	0	398	353	0	398	335	385
	Chateauroux 4	-153	31	37	-2	395	349	-2	394	332	382
	Fussy 1	-166	114	79	-14	479	399	-14	479	381	431
	Fussy 3	-90	317	277	62	682	607	62	682	589	639
	Sancerre 1	-155	18	15	-3	380	327	-3	379	309	359
	Sancerre 3	-59	249	262	92	610	580	92	609	561	611
	Sancerre 4	-146	24	31	6	387	341	6	384	321	371
	Champlitte 1	-73	127	187	-73	474	435	-73	473	434	478
	Dampierre 1	-79	48	120	-79	412	408	-79	390	390	435
	Dampierre 2	-144	-207	-37	-144	156	131	-144	135	115	159
	Vitrey 1	-108	-61	16	-108	283	256	-108	282	256	301
Walnut	Champdeniers 2	227	91	296	394	458	535	394	459	504	566
	Chateauroux 1	182	154	287	327	517	578	327	517	547	610
	Chateauroux 3	231	269	354	376	629	691	376	632	662	726
	Champlitte 2	224	-166	227	224	178	296	224	180	297	342
Poplar	Fussy 2	232	219	318	417	581	634	417	584	598	670
	Sancerre 2	414	271	508	599	632	803	599	631	764	835
	Dampierre 3	309	-132	270	309	236	401	309	210	385	445
	Vitrey 2	262	-128	250	262	215	358	262	215	357	417
Netherlands											
Walnut	Bentelo 1	-1063	248	-161	-659	646	-16	-669	615	-30	36
Poplar	Balkbrugg 1	-521	187	216	151	603	356	35	603	356	426
	Scherpenzeel 1	-756	131	140	-84	547	310	-221	547	310	384

Pre-2005 grant regime

In the pre-2005 grant regime (Table 6), the equivalent annual values of forestry systems in Spain were generally higher than those of arable systems, except where crop yields were high. The equivalent annual values of silvoarable systems were generally lower than for forestry and arable systems. In France, the equivalent annual values of arable systems were generally greater than those for wild cherry silvoarable systems, which were much greater than those for wild cherry forestry. The predicted equivalent annual values of the poplar and walnut silvoarable systems were higher than those for both forestry and arable systems. In the Netherlands, the equivalent annual values of arable systems were greatest, followed by those for silvoarable and then forestry systems.

Post-2005 grant regime

In the post-2005 grant regime (Table 6), the equivalent annual values for forestry in Spain declined in comparison with those for forestry in the pre-2005 grant regime, but increased for arable and silvoarable systems despite modulation. In France, the equivalent annual values were broadly similar to those under the pre-2005 regime, although for silvoarable systems, scenario 1 resulted in marginal reductions, while scenario 2 resulted in marginal increases in equivalent annual values. In the Netherlands, a substantial decrease in the equivalent annual values of forestry was predicted, but the change in the equivalent annual values of arable systems was marginal. For silvoarable systems, little change was predicted for scenario 1, but a small and consistent increase was predicted for scenario 2.

Farm-scale analysis

In Spain under the pre-2005 grant regime, there were no cases where establishing a silvoarable system increased farm profitability relative to the status quo (Figure 5). By contrast, under the pre-2005 grant regime, forestry was attractive in about 80% of cases. The post-2005 regime was predicted to reduce the relative profitability of forestry, but forestry still remained financially attractive on about 50% of the selected farms. In France, under the pre-2005 grant regime, silvoarable systems were predicted to increase farm profitability in approximately 50% of cases. This frequency remained similar under scenario 1 of the post-2005 grant regime, and increased to 80% under scenario 2. The proportion of farms where forestry was attractive (20%) was less than for silvoarable systems and was the same for both the pre- and post 2005 grant regimes. In the Netherlands (not shown), the introduction of forestry and silvoarable systems always reduced farm profitability under both pre- and post-2005 grant regimes.

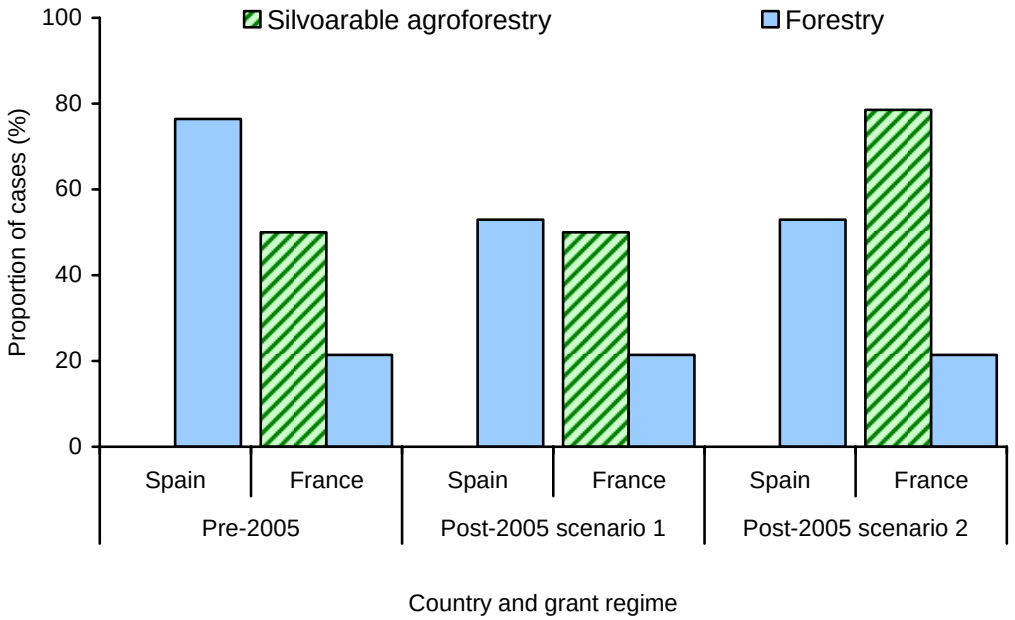


Figure 5 Proportion of cases where the net present value of hypothetical arable farms was improved by introducing silvoarable systems (113 trees ha^{-1}) and forestry systems (Spain: n =17; France: n = 14).

In Spain, the use of silvoarable systems was preferable to forestry in 12% of cases under the pre-2005 grant regime and 50% of cases in scenarios 1 and 2 of the post-2005 grant regime (Figure 6). In France and the Netherlands, farm profitability was always increased with the use of silvoarable rather than forestry systems.

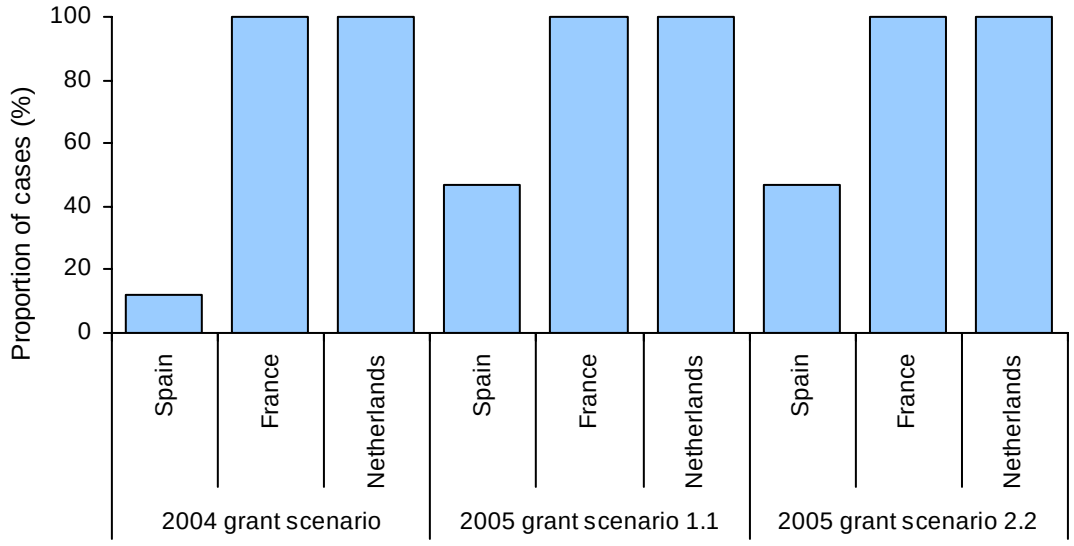


Figure 6 Proportion of cases in which the net present value of hypothetical farms was improved more by silvoarable systems (113 trees ha^{-1}) than by forestry systems (Spain: n = 17; France: n = 14; the Netherlands: n = 3)

Discussion

A process for modelling tree and crop yields, and the plot- and farm-scale economics of arable, forestry, and silvoarable systems in three European countries was developed and has been described. This process provided a systematic method for determining the effects of tree spacing, tree and crop species, and grant regime on the profitability of silvoarable systems relative to arable and forestry systems.

Biophysical modelling of yields

In Spain, the relative yields of autumn-planted crops, such as wheat, tended to be greater than those for spring-planted crops, such as sunflower (Figure 3a). As oak and stone pine are evergreen trees and competition for light was similar for both spring- and autumn-planted crops, this may have been due to greater competition for water experienced by the spring-planted crop. In France, the difference in the relative yield of the autumn- (i.e. wheat and oilseed) and spring-planted (sunflower and grain maize) crops was larger than in Spain (Figure 3b). This was probably due to reduced competition for light, because the tree species planted in France were deciduous, and hence had no leaves for a large proportion of the growing period of the autumn-planted crops. In the Netherlands (Figure 3c), the differences between relative yields of autumn-planted wheat and spring-planted forage maize under poplar followed the same pattern. Similar benefits from using autumn- rather than spring-planted crops were observed by Burgess et al. (2004) with poplar in the UK. Relative timber yields varied according to density and species (Figure 2). Timber production on a per tree basis was greater at 50 than at 113 trees ha^{-1} per tree resource use was greater at lower densities. However, per area timber production was greatest for 113 trees ha^{-1} and for wild cherry, walnut, and poplar, suggesting that higher tree densities and faster-growing species had allowed the tree component to capture a greater share of the available resources.

Although Yield-SAFE predicted lower timber yields and crop yields per hectare for silvoarable systems compared to the arable and forestry systems respectively (Figure 2), the total productivity of silvoarable systems, determined with land equivalent ratios, was predicted to be between 100 and 140% that of the monoculture systems (Figure 4). The highest ratios were obtained by integrating deciduous trees and autumn-planted crops, which were complementary in terms of light use, suggesting that silvoarable systems would be most advantageous over arable and forestry monocropping, where such species can be combined. High land equivalent ratios were also associated with the higher tree stand densities of 113 rather than of 50 trees ha^{-1}, suggesting that at 50 trees ha^{-1} silvoarable systems were sub-optimal in terms of light and water use, and that the higher tree stand density would be preferable for increased productivity. Finally, high land equivalent ratios at both tree densities were associated with faster growing trees like poplar, walnut, and wild cherry in France whilst in Spain, oak and pine systems at both densities were associated with much lower land equivalent ratios (Figure 4). The reasons for this are not clear. It may be that oak and pine growth was so slow that neither species was able to make use of available resources at the densities used in the silvoarable systems; alternatively, it is possible that crops competed more strongly for water than other trees of the same species. In either case, production benefits from oak and pine-based silvoarable systems in Spain appear to be limited

unless the density can be increased without detriment to the relative yield of either component.

Grant regimes

In the pre-2005 grant regime, support for silvoarable systems was frequently less than that for arable and forestry systems. In arable systems, crop payments in Spain (129-176 € ha^{-1}) and in France and the Netherlands (324-400 € ha^{-1}) were obtained for every year of cropping. In forestry, systems, generous schemes could make forestry payments greater then silvoarable payments. Thus in Spain, planting grants of 849-1593 € ha^{-1}, compensation payments of 225-325 € ha^{-1} a^{-1} for 20 years, and maintenance payments of 180-288 € ha^{-1} a^{-1} for five years, could be obtained. In the Netherlands, planting grants of 95% of costs up to a maximum of 1500 € ha^{-1}, compensation payments of 100 € ha^{-1} a^{-1} for five years, and maintenance payments of 545 € ha^{-1} a^{-1} for 18 years, were available. However, guidelines developed for payments on silvoarable systems resulted in disadvantages. These included termination of crop payments if cropping stopped before the tree rotation finished and reduction of crop payments by the cropped proportion of the system in France and the Netherlands, and by twice the proportion of the tree canopy in the system in Spain. Payments on the tree component did not compensate for these losses. In the Poitou Charentes and Centre regions of France, planting grants covered 50% of tree costs in the first four years of the tree rotation, but in Spain, the Netherlands and the Franche Comté region in France, the tree component received no payments at all.

Under the post-2005 grant regime, the per hectare value of the single farm payments in Spain (68-220 € ha^{-1} a^{-1}) were higher than crop payments under the pre-2005 grant regime, because payments for other farm activities were included in the calculation. In France and the Netherlands the per hectare value of the single farm payments (329-400 € ha^{-1} a^{-1}) declined marginally because of modulation. Forestry payments in Spain and the Netherlands also declined, mostly because the duration of compensation payments was reduced from 20 and 18 years respectively, to 10 years. In France, little change was evident for forestry. However, support for silvoarable systems generally improved relative to arable and forestry systems. For example, silvoarable payments for both scenarios 1 and 2 in Spain, were greatly improved in absolute terms and relative to payments for arable and forestry systems. In France and the Netherlands, the difference was less striking, although in the Netherlands, the value of silvoarable payments improved substantially relative to forestry payments. Under scenario 2, where a planting grant was added to the full single farm payment, absolute payments on silvoarable systems could marginally exceeded payments for arable systems (providing cropping did not stop before the tree rotation ended). In these circumstances, farmers might be encouraged to retain existing trees already on arable land, since they are no longer the direct cause of lost payments. However, the planting grants calculated for Spain (214-370 € ha^{-1}), France (393-793 € ha^{-1}), and the Netherlands (670-1133 € ha^{-1}) are small in proportion to the total grant payable for maintaining the land in arable production and, on their own, are unlikely to encourage widespread adoption of silvoarable systems.

Plot-scale economics
Without grants, silvoarable systems were frequently the most profitable system at the landscape test sites (Table 6). In Spain, oak and stone pine silvoarable systems were the most profitable system in six of 19 land units. In France, walnut silvoarable systems were the most profitable system in four out of four land units, poplar silvoarable systems the most profitable system in two out of four land units, and wild cherry silvoarable systems the most profitable system in nine out of 12 land units. In the Netherlands, poplar silvoarable systems were the most profitable system in two out of two land units.

However, the pre-2005 grant regime altered the profitability of silvoarable systems, relative to arable and forestry systems (Table 6). This was especially the case in Spain, where silvoarable systems became the least profitable system on all 19 land units. In France, walnut silvoarable systems remained the most profitable system on each of the four land units and poplar silvoarable profitability increased relative to forestry to also became the most profitable system on the four land units. Wild cherry silvoarable systems became less profitable then arable systems, but remained more profitable than forestry systems on all 12 land units. In the Netherlands, poplar silvoarable systems became less profitable than arable systems and more profitable then forestry systems; the relative profitability of walnut silvoarable systems remained less profitable than the arable system, but more profitable than the forestry system.

Under scenarios 1 and 2 of the post-2005 grant regime, support for silvoarable systems was generally predicted to be more equitable in comparison with the pre-2005 grant regime. Hence, in Spain, the profitability of oak and stone pine silvoarable systems now frequently exceeded that of forestry systems and became only marginally less than that of arable systems on all 19 land units. Since oak and stone pine are important for their landscape value, the small difference between the equivalent annual values of the silvoarable and arable systems (5-54 € ha^{-1} a^{-1}) represents the minimum level of additional support, perhaps as an agri-environment payment, required for silvoarable systems to become financially attractive to farmers. In France, the relative profitability of silvoarable, arable, and forestry systems for scenario 1 was similar to that in the pre-2005 grant regime, and increased marginally for scenario 2, so that wild cherry silvoarable systems also became the most profitable systems in six of 12 land units. Walnut and poplar silvoarable systems continued to be the most profitable systems in all eight land units, in both scenarios 1 and 2, demonstrating the importance of using high value (walnut) or short rotation (poplar) trees in silvoarable systems. In the Netherlands, the relative profitability of silvoarable systems in comparison with the arable and forestry systems remained unchanged under both scenarios. The disadvantage of using long rotation and low value timber was illustrated by the use of walnut in the Netherlands. The importance of fully understanding all the costs associated with changing land use was illustrated by the high opportunity cost of losing land for slurry manure application, which made forestry relatively unprofitable under all the grant regimes.

Farm-scale economics
The effect of using silvoarable agroforestry was examined firstly in terms of its impact on the profitability of hypothetical farms and secondly as a means of establishing trees

on farms. Under the pre-2005 grant regime in Spain, it was unprofitable to replace arable systems with silvoarable systems. This was due to low timber volume and value, and especially due to the lack of tree grants and the loss of arable area payments under the canopy-area based calculation. Under the post-2005 grant regime, replanting arable land with silvoarable systems still reduced farm profitability. By contrast, in France, establishing walnut and poplar silvoarable systems increased farm profitability under both the pre- and post-2005 grant regimes. Wild cherry silvoarable systems generally decreased farm profitability, due to low timber values and long rotations, except occasionally under scenario 2 of the post-2005 grant regime. In the Netherlands, introducing silvoarable systems in place of arable systems reduced farm profitability under both the pre- and the post-2005 grant regimes.

Under the pre-2005 grant regime in Spain, forestry generally provided a more cost effective means of establishing trees on farms than silvoarable agroforestry, because of high levels of support for forestry systems. However, under the post-2005 grant regime, it was predicted that silvoarable agroforestry would become the most profitable means of establishing trees on farms in a substantial number of cases. In France and the Netherlands, silvoarable systems with walnut, wild cherry, and poplar provided the most profitable means of establishing trees on farms, irrespective of grant regime used.

Conclusions and recommendations

Land equivalent ratios developed using Yield-SAFE predictions were consistently above one, indicating that growing trees and crops in silvoarable systems was more productive than growing them separately. Conditions that most favoured high land equivalent ratios appeared to include the use of relatively high tree-densities to make full use of available resources, the use of deciduous trees and autumn-planted crops to make complementary use of light, and high soil water availability to ensure that extra biomass production could be sustained. Conversely, low land equivalent ratios were associated with low tree density, evergreen trees, spring-planted crops, and low soil water availability.

The financial predictions made by FarmSAFE indicated that silvoarable systems were most attractive where both components of the system were profitable as moncultures, since an unprofitable, or relatively unprofitable component, also reduced the profitability of the mixed system. In addition, the relative profitability of silvoarable systems tended to be maximised if the profitability of the forestry and arable systems was similar. Under the two scenarios proposed for the post-2005 grant regimes, it was predicted that silvoarable systems with walnut and poplar in France could provide a profitable alternative to arable or forestry systems. The importance of using high value trees such as walnut, or short rotation trees such as poplar, was illustrated by use of these trees in France. In Spain, it was predicted that holm oak and stone pine silvoarable systems would cause only small reductions in crop yields, relative to those in arable systems. Since these trees are of ecological and landscape importance for example, in areas of open woodlands (dehesas), rather than of productive importance, additional support in the form of an agri-environment payment could be justified. A moderate annual amount would be sufficient to overcome income losses caused by yield reductions and encourage tree establishment for non-productive benefits. In the Netherlands, the low value of timber and an opportunity cost, assumed because of the

loss of arable land for slurry manure application, made both silvoarable and forestry systems relatively unattractive in comparison with arable systems.

A number of recommendations regarding further research can be made. Predictions are subject to uncertainty and this could be examined using sensitivity analysis or stochastic modelling. Certain baseline data should also be re-examined. For example, the recorded value of walnut timber in the Netherlands and France differed greatly, even though both countries are part of a free-trade zone. In the Netherlands, assumptions regarding slurry manure should be re-examined, since these greatly undermine the profitability of tree-based systems. In Spain, assumptions regarding beating-up, tree management and the availability of grants should be re-assessed. Tree mortality is likely to be high due to difficult conditions, and pruning and thinning costs, whilst valid for traditional management of trees in dehesas, may not be valid for forestry and silvoarable systems, even if these are established in such areas. Finally, the post-2005 grant regime should be re-assessed, as the impact of the European Union's rural development strategy will become clearer in time.

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