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Implementation and calibration of the parameter-sparse Yield-SAFE model to predict production and land equivalent ratio in mixed tree and crop systems under two contrasting production situations in Europe

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ABSTRACT

Silvoarable agroforestry, the integration of trees and arable crops on the same area, has the potential to offer production, ecological, and societal benefits. However, the uptake of such systems in Europe has been limited by a combination of unsupportive policies and uncertainty concerning their productivity, profitability, and environmental impact. Faced with a lack of experimental data, the parameter-sparse Yield-SAFE model offers one method for generating plausible yield data and improving understanding of production in mixed tree–crop systems under European conditions. The applicability of the model was examined by: (i) selecting two contrasting sites in France and the UK with measured agricultural, silvoarable and/or forestry data, (ii) implementing the model in a software package, and (iii) inputting data and parameters on the climate, soils, management regime, and tree and crop types. Following calibration, Yield-SAFE provided credible descriptions of measured arable and tree (*Populus* spp.) yields in the monoculture and silvoarable systems at the two sites. An examination of the response of the model to changes in model parameters and environmental and management data showed that silvoarable crop yields were most sensitive to variations in tree parameters. Increased soil depths increased timber yields, and increasing stand density increased stand volume whilst decreasing individual tree volume. In all the simulations, the model predicted greater efficiency in use of land, i.e. greater land equivalent ratios, when trees and crops were combined rather than grown as sole crops. These results, supported by the sparse experimental data available, indicate that agroforestry provides a method of increasing food, timber and biomass production from limited land resources in Europe.

1. Introduction

The European Commission's Rural Development Regulation for 2007–2013 (Commission of the European Union, 2005) has introduced measures to promote agroforestry because of its "high ecological and social value" and because of the potential of producing high-quality forestry products. This is an exciting development as agroforestry systems have often been neglected because of the administrative separation of forestry and agriculture departments (McAdam et al., 2009). One form of agroforestry practice is silvoarable agroforestry where arable crops are grown between widely spaced trees (Burgess et al., 2004). Such arable cultivation is practiced at some time on about 10–16% of the 3 million ha of the dehesas of Spain and the montados of Portugal (Eichhorn et al., 2006). An important role of the cultivation is to control the invasion of shrubs which are not grazed by livestock. Silvoarable agroforestry integrating poplar trees with cereal crops is practiced in the Po Valley region of Italy, and such systems have been used in the UK (Eichhorn et al., 2006). In France, about 2000 ha of silvoarable systems were planted in the winter of 2007–2008 and a further half a million hectares could potentially be planted. For Europe as a whole, it has been estimated that approximately 56% of arable land could support silvoarable systems with about 40% benefitting from improvement of an existing environmental problem (Reisner et al., 2007). However, there is limited knowledge on the productivity of these mixed tree–crop systems, in

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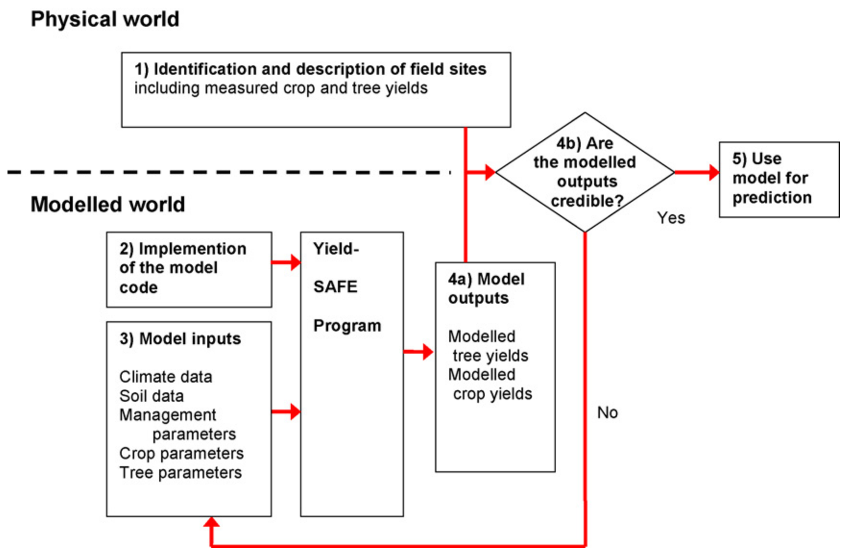

Fig. 1. Outline of the modelling process.

comparison to tree or crop monocultures, under European conditions.

Modelling can help to generate insight into the productivity of agroforestry systems, based on robust principles governing resource acquisition and use efficiency in crop and tree systems (Van Ittersum and Rabbinge, 1997). To apply those principles to agroforestry systems, the Yield-SAFE model (Van der Werf et al., 2007) was conceptualized to provide a parameter sparse but eco-physiologically based simulation model for tree and crop growth in agroforestry systems. The model, which operates on a daily time-step, simulates growth and dry matter accumulation of trees and crops over the whole growing cycle of a tree stand. For each day, the model calculates light interception by the trees and the crop, and derives the potential dry matter production. The actual, water-limited, dry matter production is then derived by taking into account water availability for the tree and the crop, using a simple water balance model. Growth and senescence of the leaf cover of the trees and crops is calculated on a daily basis, based on simulation of phenological processes, driven by temperature, and the assimilates available for growing leaves. The Yield-SAFE model was designed to be "as simple as possible". Thus, the model consists of only seven differential equations, for (1) crop leaf area, (2) tree leaf area, (3) crop biomass, (4) tree biomass, (5) number of tree branches, (6) soil water, and (7) temperature sum. Despite the parsimonious modelling philosophy, the Yield-SAFE model still has 22 ecophysiological parameters characterizing the plant–environment interactions, and further parameters and forcing functions representing management. The only meteorological inputs are daily mean temperature, daily incoming radiation, and daily precipitation. A concise description of the equations and parameters is given in Van der Werf et al. (2007). This paper advances that work by aiming to demonstrate the applicability of the Yield-SAFE model to: (i) simulate existing systems at two contrasting sites and (ii) predict the responses of trees and crops in novel arable, forestry and agroforestry systems.

Given the parameter requirements of Yield-SAFE, and the scarcity of agroforestry experiments in Europe, parameterisation is a non-trivial task. Here, we provide an example of how the model the Yield-SAFE model was parameterised in an iterative process, using crop, tree, soils and climate data from two contrasting sites in Europe. One site is based in a relatively cool Atlantic climate, and the other site in a Mediterranean climate where radiation, temperature and drought-stress levels are greater. After model parameterisation, and evaluation of the main model results, a sensitivity analysis was conducted to determine the main factors affecting the productivity of agroforestry, compared to monocultures of trees and crops.

2. Methods

The broad method of demonstrating the applicability of the Yield-SAFE model can be described as a five-stage process (Fig. 1). The first three stages were (i) identifying and describing two field sites with measured data, (ii) implementing the Yield-SAFE model code described by Van der Werf et al. (2007), and (iii) selecting model inputs for the climate, soil, crop, tree and management regime (Fig. 1) and a first estimation of model ecophysiological parameters based on bibliography and expert knowledge. The fourth stage comprised a period of iteration where up to three parameters were modified until the outputs of the model matched the measured outputs. These stages are described within this method section. Using parameter values that resulted in modelled yields similar to the measured yields, the model was then used to predict the tree and crop yields for different tree densities and soil depths. This process is described in Section 3.

2.1. Identification of field sites

The first stage was to identify two European sites where there was a series of silvoarable tree and crop yield data. The two sites were Vézénobres in the Languedoc–Roussillon region of southern France, and Silsoe in the county of Bedfordshire in Eastern England (Table 1). Both are located on land that is typically used in arable production in their respective areas. Although the sites were chosen because of the availability of field measurements, there were still gaps in the data. At the Vézénobres and Silsoe sites, data were available for the early stage of a tree rotation, but the trees had not been harvested. Because of this, some of the tree and crop data had to be derived from a synthesis of field measurements, statistical data, and expert opinion.

2.1.1. Vézénobres

The Vézénobres site in Southern France is located in a region where half the land is used for agriculture and half for forestry; typical agricultural crops are vines, forage crops and cereals. In 1996, a 1.57 ha silvoarable and forestry experiment was planted using 5 m un-rooted sets of poplar (*Populus* spp.) clones I-214 and I-4551. The trial included a forestry (7 m × 7 m spacing; 204 trees ha^{-1}) and a

Table 1
Location and description of the trees in the forestry and agroforestry system at Vézénobres and Silsoe. The actual and modelled cropping systems are indicated.

	Vézénobres, France	Silsoe, UK
Latitude; longitude	44°3′N; 4°8′E	52°0′N; 0°26′W
Altitude (m)	103	50
Trees planted	1996	1992
Meteorological conditions		
Mean annual solar radiation (MJ m^{-2})	5121	4356
Mean annual temperature (°C)	14.4	9.1
Mean annual rainfall (mm)	1000	611
Forestry system		
Components	Widely spaced poplar (*Populus* spp.) with cultivated but uncropped alleys	Widely spaced poplar (*Populus* spp.) with cultivated but uncropped alleys
Tree row orientation	North–South	North–South
Area (ha)	0.42	0.84
Tree spacing (m)	7 × 7	10 × 6.4
Tree density (ha^{-1})	204	156
Silvoarable system		
Components	Widely spaced poplar hybrids with cultivated cropped alleys	Widely spaced poplar hybrids with cultivated cropped alleys
Tree row orientation	North–South	North–South
Area (ha)	1.15	1.69
Tree spacing (m)	16 × 4.5	10 × 6.4
Tree density (ha^{-1})	139	156
Tree strip width (m)	1	2
Arable system		
Actual crop species and rotation	Durum wheat, asparagus, sorghum and fallow	Cereals and break crops
Modelled crop species and rotation	Autumn-sown continuous durum wheat	Autumn-sown: wheat, wheat, barley, oilseed rape

silvoarable (139 trees ha^{-1}) area. The tree rows in the silvoarable area were oriented in a north-south direction with a spacing of 4.5 m × 16 m (including a 1-m wide tree strip). The owner of the site had leased the intercrop area of the silvoarable system to a farmer, who also managed the arable control. There was an agreement that the owner should prune the trees so that overhanging branches would not impede the movement of agricultural machinery in the intercrop area. Otherwise the management of the forestry and arable plots was typical for forestry and arable systems in the area. The trees at the site potentially have access to a high water table.

In Vézénobres, the height and diameter of poplar clone I-214 were recorded annually from planting in 1996 to 2005. The trees in silvoarable plots were initially smaller than those in forestry plots, but 9 years after planting they were of similar size. Expert opinion was used to derive estimates of the timber volumes of the silvoarable (0.98 m^3 tree^{-1}) and forestry (0.88 m^3 tree^{-1}) trees at a harvestable age of 15 years (Fig. 2a). The crops grown in the silvoarable system were predominantly durum wheat (*Triticum durum* Desf.), but also included 1 year of asparagus and sorghum and 2 years of fallow. Hence a combination of assumed and measured yields were used to derive a yield profile of the arable crops that decreased from a relative value of 90% in year 1 to 30% in year 12 (Fig. 2c), after which it was assumed that no intercrop would be grown. A typical yield for durum wheat in the area (4.0 t ha^{-1}) was used as a reference yield for the arable plot.

2.1.2. Silsoe

The Silsoe site in Eastern England is located in an area dominated by cereal, oilseed rape and protein field crops (64% of the agricultural area); woodlands occupy only about 7% of the area. The experimental silvoarable site was managed as part of the UK silvoarable network and is fully described by Burgess et al. (2004). The silvoarable and "forestry" components covered 2.5 ha and comprised three replicate blocks that included each combination of four poplar hybrids (Beaupré, Trichobel, Gibecq, and Robusta) and one forestry and two silvoarable treatments. Between March and April 1992, in both the forestry and silvoarable treatments, poplar was planted at a spacing of 10 m × 6.4 m (156 trees ha^{-1}) with rows oriented north-south. Planting stock consisted of 1.5–2.0 m unrooted sets which were inserted to a depth of 0.6 m in the soil. The "intercrop" area within the "forestry" treatment was kept fallow by regular cultivation, whilst the silvoarable area was cropped on an annual basis. Following poor crop yields in the initial 3 years, a wheat (*Triticum aestivum* L.) crop was harvested in 1995, 1996 and 1997, followed by field beans (*Vicia faba* L.), two more wheat crops, a bare-fallow, barley (*Hordeum vulgare* L.), and field beans. Arable control plots, located at least 15 m from the nearest poplar, were managed in the same way as the silvoarable intercrop. Yield data reported in Burgess et al. (2004) show that the interference by the trees on crop growth in the arable control plots has been minimal.

Tree and crop measurements taken at Silsoe showed that 12 years after planting, timber volume was 0.35 m^3 tree^{-1} in the forestry plots and 0.25 m^3 tree^{-1} in the silvoarable plots (Fig. 2b) (Burgess et al., 2003, 2004). The dimensions and volumes of poplar trees in the forestry treatments were between those for empirical growth models of poplar for Yield Classes 12 and 14 (Christie, 1994). Mean timber volumes for Yield Classes 12 and 14 were therefore used to predict growth beyond the period provided by field measurements to final harvest. This provided a reference timber volume of 2.41 m^3 tree^{-1} in the forestry plot in year 30. In the case of the silvoarable treatment, the current yield was similar to the growth shown for Yield Class 10. This then provided a timber volume of 1.85 m^3 tree^{-1} in the silvoarable plot in year 30. Because the timeliness of some crop management operations was sub-optimal, resulting in late planting or planting into wet seedbeds, arable crop yields were often below commercial levels. Therefore the yield for the intercrop was expressed as a proportion of crop yield in the arable plot. This showed a yield decline from about 80% from years 1 to 4 to 70% between years 4 and 8, and 60% between years 9 and 12 (Fig. 2d). The reference yields for control arable crops of wheat (8.23 t ha^{-1}), barley (6.83 t ha^{-1}) and oilseed (3.44 t ha^{-1}) were derived from statistical data for yields on Bedfordshire clay and are typical of the area (Lang, 2004).

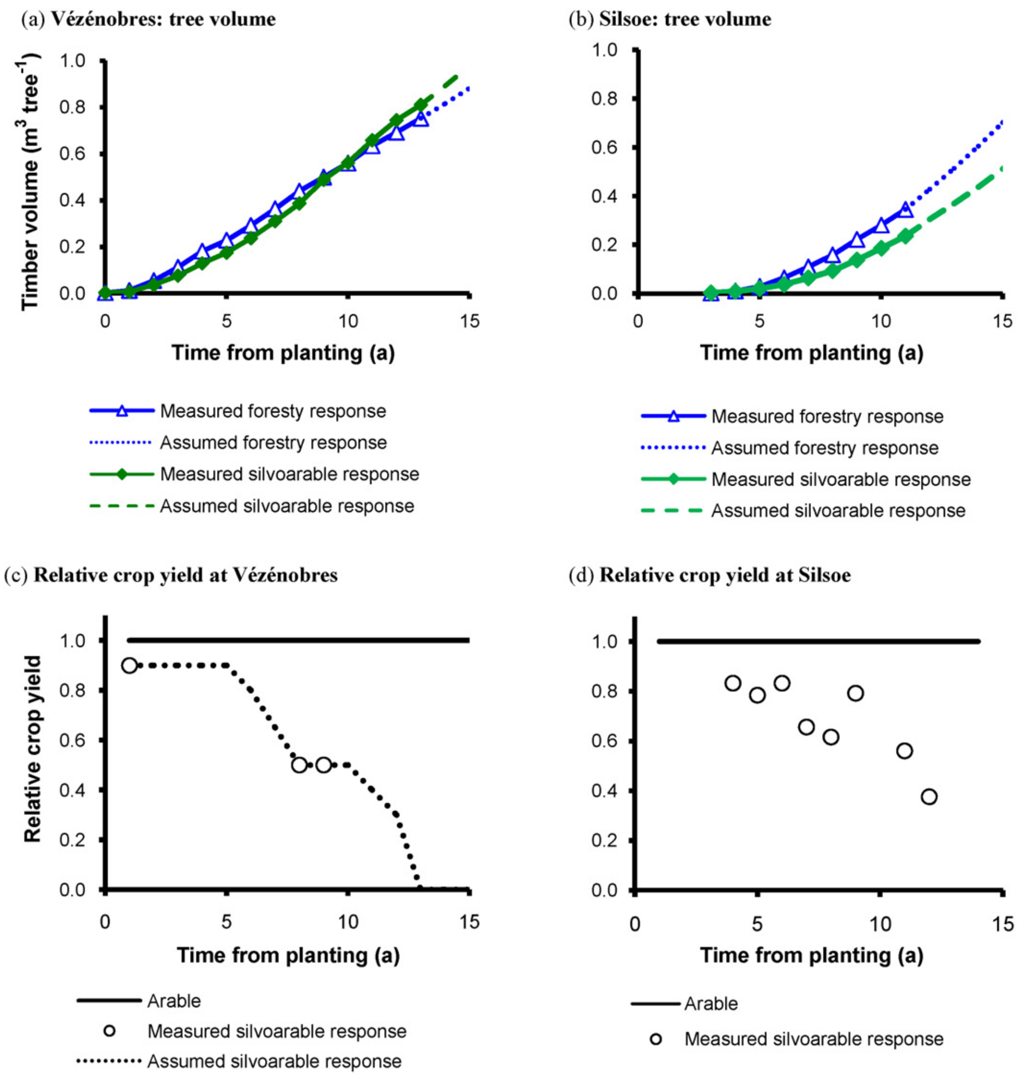

Fig. 2. Measured (a) silvoarable and forestry timber yields at Vézénobres, (b) forestry timber volumes at Silsoe, (c) relative crop yields at Vézénobres, and (f) relative crop yield at Silsoe.

2.2. Implementing Yield-SAFE model code

The Yield-SAFE equations developed to predict crop and tree yields in arable, forestry and silvoarable systems, described by Van der Werf et al. (2007), were implemented in a Microsoft Excel© spreadsheet platform called Plot-SAFE by Burgess et al. (2004a). The core equations were implemented in a single worksheet called "Yield-SAFE", which uses default values for the meteorological, soil, tree, and crop parameters from a second worksheet called "Bio-parameters". A third worksheet called "Crop-manager" describes the overall system including the crop rotation and tree management. A description of Plot-SAFE and a user guide for this version are available from Cranfield University (Graves and Burgess, 2007).

2.3. Selection of model inputs and parameters

The third stage of the process was to input data relating to (i) meteorology, (ii) soil, (iii) site management, (iv) the tree species, and (v) the crop. These are described in turn.

2.3.1. Meteorological data

The required meteorological inputs to the model were daily solar radiation, temperature, and rainfall. Data for Vézénobres consisted of a 12-year dataset from a local site, from January 1996 to December 2008; the first year and the last 2 years of this data were repeated to provide a 15-year dataset. For Silsoe, 30 years of data were developed using a weather generator, CLIGEN 5.2 (United States Department of Agriculture, 2005). The reference values (Global Data Systems, 2005) for Silsoe were generated from a weather station in Cranfield, approximately 15 km north–west.

The mean annual solar radiation and mean air temperature at Vézénobres (5121 MJ m^{-2}; 14.4 °C) were greater than at Silsoe (4356 MJ m^{-2}; 9.1 °C). The mean annual rainfall at Vézénobres (1000 mm) was also greater than at Silsoe (611 mm). However the seasonal distribution of the rainfall at Vézénobres was more uneven, with rainfall primarily occurring during the winter months. The data for both sites are summarised in Table 1.

2.3.2. Soil data

The soils were classified in terms of their texture, and their hydraulic properties were derived from Wösten et al. (1999). In Vézénobres, the soil was medium-textured and because of the presence of a relatively high water table, the effective soil depth in terms of the model was assumed to be 2.0 m (Table 2). The effect of assuming a large soil depth was to increase the amount of soil water available to the trees and the crop. In Silsoe, the soil was clay (Burgess et al., 2004) and classified as "fine-textured" with a depth of 1.5 m.

Table 2
Soil parameters assumed for the two sites.

Parameter	Symbol	Unit	Vézénobres	Silsoe
Soil type			Medium	Fine
Initial water content	θ_0	mm mm^{-1}	0.552	0.552
Saturation water content	θ_s	mm mm^{-1}	0.439	0.520
Residual water content	θ_r	mm mm^{-1}	0.010	0.010
Depth of soil	D	m	2.0	1.5
Water tension at field capacity	pF_{FC}	log(cm)	2.3	2.3
Critical pF value for evaporation	$(pF_{crit})_E$	log(cm)	2.3	2.3
pF where soil evaporation = 0	$(pF)_{E=0}$	log(cm)	4.2	4.2
Van Genuchten parameter	α	cm^{-1}	0.0314	0.0367
Van Genuchten parameter	n		1.1804	1.1012
Parameter affecting drainage rate below root zone	δ		0.07	0.07
Soil hydraulic conductivity at saturation	K_S	mm day^{-1}	12.1	24.8
Potential evaporation per unit energy	δ_{eva}	mm MJ^{-1}	0.15	0.15

2.3.3. Management parameters

The management parameters within the Yield-SAFE model relate to the initial tree stand density, and the management of the trees and the crops (Tables 1, 3 and 4). The crop management parameters comprised the choice of crop (Table 1) and the date of sowing (Table 4). The management parameters for the forestry systems were selected to be as close as possible to actual practice as determined during field visits and discussions with farmers at each site. At Vézénobres and Silsoe, the forestry systems were planted at 204 and 156 poplar trees ha^{-1} respectively.

The management parameters related to the trees include the timing and extent of pruning (Table 3). In many agroforestry systems, side branches arising from the main stem below a certain height (the bole height) are pruned in order to maximise the volume of knot-free timber. At each site, it was assumed that pruning took placed in increments of 1.5 m, ensuring that the bole height was never more than 50% of the tree height, up to a maximum height of 8 m (Table 3). The proportion of shoots (π_s) pruned on each occasion was also assumed.

The silvoarable systems were parameterised so that they integrated the tree species of the forestry system with the crop species and rotation of the arable system. In Vézénobres and Silsoe, the trees were arranged in rows, and the intercrop area was calculated by subtracting a 2-m wide strip of aggregate tree row length in each system from the total area of the system. In Vézénobres, these dimensions resulted in an intercrop area of 87.5% (16-m row width) and in Silsoe 80% (10-m row width).

2.3.4. Tree and crop parameters

The parameters used to describe growth of different tree and crop species in Yield-SAFE were determined from published material and the calibration of the model for “potential” tree and crop yields (Van Ittersum and Rabbinge, 1997). An initial calibration of Yield-SAFE for “potential” monoculture yields was undertaken against datasets of timber volume and crop yields under high yielding conditions in Atlantic and Mediterranean zones assuming that light and temperature, but not water, limited growth within the model. The tree parameters included initial values for the num-

Table 3
Tree parameters used in the Yield-SAFE model for poplar in Vézénobres and Silsoe, a Mediterranean and Atlantic climate respectively.

Parameter	Symbol		Vézénobres	Silsoe
Tree management				
Tree species			Poplar	Poplar
Day of year for planting	t_{plant}	DOY	2	2
Day of year for pruning	t_{prune}	DOY	350	350
Pruning height increment	h_{prune}	m	1.5	1.5
Proportion of shoots removed per prune	π_s		0.1	0.1
Maximum bole height/tree height	$(H_{bole}/H)_m$		0.5	0.5
Maximum bole height	$(H_{bole})_m$	m	8	8
Initial conditions				
Number of shoots per tree	$(N_t)_0$	tree^{-1}	1.7938	0.6225
Biomass of tree	$(B_t)_0$	g tree^{-1}	100	100
Bole height	$(H_{bole})_0$	m	0	0
Leaf area of tree	$(LA_t)_0$	m^2 tree^{-1}	0	0
Parameters				
Radiation use efficiency	ε_t	g MJ^{-1}	1.1900	1.4086
Light extinction coefficient	k_t		0.8	0.8
Maximum leaf area of single shoot	A_m	m^2	0.025	0.05
Time constant of leaf area growth of shoot	τ_t	day	10	10
Relative attrition rate of tree biomass	a	day^{-1}	0.0001	0.0001
Day of year for bud burst	$t_{budburst}$	DOY	100	100
Day of year for leaf fall	$t_{leaffall}$	DOY	300	300
Exponent relating tree diameter to height	q		1	1
Form factor	F		0.367	0.367
Maximum number of shoots per tree	N_m	tree^{-1}	10000	10000
Density of dry timber	ρ_{timber}	g m^{-3}	410,000	410,000
Ratio of tree height to tree diameter	σ_{height}		68.556	68.556
Ratio of canopy width to depth	σ_{canopy}		0.6	0.6
Critical pF value	$(pF_{crit})_t$	log(cm)	4.0	4.0
pF value at permanent wilting point	$(pF_{pwp})_t$	log(cm)	4.2	4.2

Note: In the default calibrations, the value of π_s was fixed to 0.

Table 4
Crop parameters used in the Yield-SAFE model.

Species			Wheat, durum wheat and oats	Oilseed rape
Management				
Day of sowing	t_s	DOY	−45	−116
Day of harvest (if S_h not reached)	t_h	DOY	300	225
Initial conditions				
Above-ground dry mass	$(B_c)_0$	g m^{-2}	10	10
Leaf area of crop	$(L_c)_0$	m^2 m^{-2}	0.1	0.1
Partitioning factor to leaves	$(\rho_l)_0$		0.8	0.8
Parameters				
Radiation use efficiency of the crop	ε_c	g MJ^{-1}	1.34	0.8
Light extinction coefficient	k_c		0.7	0.7
Critical pF value for transpiration	$(pF_{crit})_c$	log(cm)	2.9	2.9
pF value when transpiration = 0	$(pF_{pwp})_c$	log(cm)	4.2	4.2
Specific leaf area	σ	m^2 g^{-1}	0.005	0.02
Heat sum at harvest	S_h	°Cd	1312	2000
Base temperature	T_b	°C	5	5
Heat sum at emergence	S_{emerge}	°Cd	57	79
Heat sum when partitioning leaves starts to decrease	S_1	°Cd	456	500
Heat sum when partitioning to leaves ceases	S_2	°Cd	464	1300

Barley was assumed to have the same parameters as wheat, except the DOY_{sowing} was −60.

ber of shoots per tree, biomass, and leaf area, and fixed values for radiation use efficiency, light extinction coefficient, and the relative attrition rate of tree biomass (Table 3). The crop parameters included initial values for leaf area and above-ground dry mass, and fixed values for radiation use efficiency, light extinction coefficient, specific leaf area, base temperatures and thermal time requirements (Table 4).

2.4. Calibration of model by modification of three parameters

The fourth step in using the model was to adjust the value of no more than three parameters to improve the agreement between the model outputs and the available data. The three parameters that could be altered were the transpiration coefficient (the amount of water transpired per unit of above-ground (crop) or woody (tree) biomass), the harvest index, and a management factor (Table 5). The default value for the transpiration coefficient (0.28–0.65 m^3 kg^{-1}) varied with crop species (C3 plants v C4 plants) and the humidity of the agro-ecological zone (humid Atlantic zone v dry Mediterranean zone). Within the calibration exercise, the values for transpiration for an individual species were allowed to vary within this range. The default value for the harvest index for the tree (proportion of above-ground biomass allocated to timber) was 0.5. Lastly a management factor (range: 50–100%), which was assumed to act directly on the radiation use efficiency could also be altered. The final values used were considered to be within acceptable physiological boundaries (Graves, 2005). This iterative process ensured that the mean modelled yield of the monoculture arable crops matched the reference value for those crops, and the modelled monoculture tree yield matched the reference tree yield at final harvest.

2.5. Model predictions and sensitivity analysis

Once calibrated, simulations were undertaken to determine the sensitivity of the modelled tree biomass to changes in management, such as tree spacing, and environmental conditions, such as soil depth. The densities examined varied from 50 to 1000 trees ha^{-1} for both the forestry and silvoarable systems, and the three soil depths examined were 0.5, 1.5, and 2.5 m. In order to simplify the analysis of the results, no thinning or pruning was assumed in the sensitivity analysis.

It has been common practice in agroforestry and intercropping studies to consider yield benefits in terms of the land equivalent ratio (LER) (Mead and Willey, 1980; Ong, 1996; Dupraz, 1998). The LER is typically defined as "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 can be calculated using:

$$\mathrm{LER} = \frac{\text{tree silvoarable yield}}{\text{tree monoculture yield}} + \frac{\text{crop silvoarable yield}}{\text{crop monoculture yield}} \quad (1)$$

A second set of simulations was undertaken for a sensitivity analysis, to investigate which parameters dominated LER. To do this, the parameter values were altered by plus and minus 10% of their

Table 5
Reference calibrations and assumed values for the transpiration coefficient, harvest index and the management factor for (a) tree species and (b) crop species at the three sites.

(a) Tree parameters Tree species	Symbol	Unit	Vézénobres Poplar	Silsoe Poplar
Time of clear fell		year	15	30
Reference yield		m^3 tree^{-1}	0.88	2.41
Transpiration coefficient	γ_t	m^3 kg^{-1}	0.440	0.280
Harvest index	HI	%	54	43
Management factor	M	%	100	100

(b) Crop parameter		Unit	Vézénobres	Silsoe		
Crop species			Wheat	Wheat	Barley	Oilseed rape
Reference crop yield	t_s	t ha^{-1}	4.00	8.23	6.83	3.44
Transpiration coefficient	γ_c	m^3 kg^{-1}	0.440	0.300	0.318	0.420
Harvest index	HI	%	42	57	46	29
Management factor	M	%	76	100	100	51

nominal values and the resulting tree and crop yield stored. Having calculated the LER, the sensitivity was calculated using:

$$\frac{\Delta y}{\Delta pi} = \frac{y(pi + \Delta pi) - y(pi - \Delta pi)}{2\ \Delta pi} \quad (2)$$

where $y(pi + \Delta pi)$ and $y(pi - \Delta pi)y$ was the model output (e.g. LER) when only the ith parameter was changed by amount Δpi whilst the other parameters were kept at their nominal values. To avoid scale effects, the relative sensitivity or elasticity (e_{LER}) of LER for a specific parameter pi with nominal values $\overline{pi}$ and $\overline{LER}$ was calculated using:

$$e_{\mathrm{LER}} = \frac{\Delta \mathrm{LER}}{\Delta pi}\,\frac{\overline{pi}}{\overline{\mathrm{LER}}} \quad (3)$$

The systems assumed for the sensitivity analysis were identical to those developed for Vézénobres and Silsoe, except that continuous wheat was assumed for the duration of the rotations.

3. Results

3.1. Model outputs

Because the yield of the monoculture arable crop was calibrated to the reference value, the mean values for the crop yields matched the assumed reference values. However the annual variation in the weather data resulted in substantial variation in the predicted annual yields. Because the relative inter-annual variation in rainfall was greater than that for temperature and solar radiation, the yields at Silsoe were more closely correlated with the rainfall during the cropping season (Fig. 3) than levels of solar radiation or temperature. By contrast, arable crop yields at Vézénobres (data not shown) did not show this response, possibly because of the larger soil depth assumed and the greater autumn and winter rainfall.

3.1.1. Tree yields in a monoculture

As described previously, the tree models were calibrated so that the forestry monoculture gave the same final yield as the measured timber yields, e.g. 0.88 m^3 $tree^{-1}$ at 204 trees ha^{-1} at 15 years after planting at Vézénobre, and 2.41 m^3 $tree^{-1}$ at 156 trees ha^{-1} at 30 years after planting at Silsoe. The results for Vézénobres showed that the Yield-SAFE model predicted lower annual timber increments than those measured during initial growth, before converging on the measured value in the final year of the tree rotation in year 15 (Fig. 4a); by contrast the predicted and reference results for the forestry system at Silsoe were more closely matched (Fig. 4d). The modelled under-prediction of timber volumes in the initial period of tree growth is probably a result of constraints within the Michaelis–Menten function of the Yield-SAFE model.

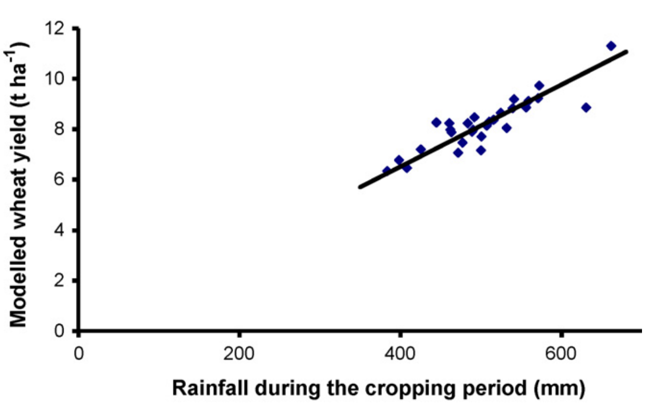

Fig. 3. Relationship between the modelled crop yield of wheat and the rainfall in the period from crop sowing to crop harvest for the Silsoe site (Yield (in t ha^{-1}) = 0.01629 (±0.00018), Rainfall (in mm); n = 29; r^2 = 0.76).

3.1.2. Crop and tree yields in silvoarable systems

Following calibration for the monoculture system, the Yield-SAFE model was used to describe the annual change in tree and crop yields within the experimental agroforestry systems at Vézénobres (139 trees ha^{-1}) and Silsoe (156 trees ha^{-1}). At both sites, the model predicted a decline in relative crop yields that was similar to the experimental data (Fig. 4c and f). The decline in crop yields was rapid because the fast growth of the poplars meant that they intercepted a major proportion of the incoming light early in the tree rotation.

At Vézénobres the modelled tree yields in the agroforestry system showed a similar pattern to the experimental data (Fig. 2a) in that the timber volume per tree in the silvoarable system eventually exceeded that of the forestry trees (see Fig. 4a and b). One reason for this is that the silvoarable trees were planted at a lower density than the forestry trees and were eventually able to intercept more light on a per tree basis. The final yield from the Yield-SAFE prediction (0.99 m^3 $tree^{-1}$) also closely matched that assumed for the silvoarable treatment (0.98 m^3 $tree^{-1}$). By contrast, at Silsoe, the modelled timber volumes in the silvoarable system (Fig. 4e) remained below those in the forestry system (Fig. 4d), even though the tree densities were the same in both systems, because the yield in the agroforestry system was reduced by crop competition for water (Burgess et al., 2004). These modelled relative yields were similar to the relative yield differences developed for Silsoe using the Yield Class data (Fig. 2c) where final timber yields were also lower in the silvoarable treatment than in the forestry treatment. However, although the final Yield-SAFE prediction for the silvoarable system at Silsoe (2.20 m^3 $tree^{-1}$) was greater than that for the assumed response of the silvoarable treatment (1.85 m^3 $tree^{-1}$) which is based on an empirical poplar growth model of Yield Class 10 (Fig. 4e), it is worth noting that this assumed silvoarable response is based on the early growth of the trees, and is also uncertain. For example, it is possible that as the silvoarable trees become larger and rooting depth increases, the effect of crop competition for water may be reduced, so that the silvoarable tree growth then exceeds the currently assumed response. This would prompt the need to increase the assumed Yield Class for the silvoarable treatment, which would then more closely match the Yield-SAFE prediction.

3.2. Model predictions

Once it was clear that the Yield-SAFE model was capable of producing credible simulations, the model was used to predict the responses of tree and crop yields to different tree densities and rooting depths.

3.2.1. Response to tree density

When the water component of the Yield-SAFE model was turned-off, the predicted tree volumes from a forestry and silvoarable treatment at the same tree density resulted in the same tree yield (Fig. 5a, b, d and e). This would be expected as the model assumes that the only effect of the understorey crop on tree yield is to alter the available water in the soil. As would be expected the volume of an individual tree decreased as the tree density increased, and the stand volume reached a plateau at high tree densities.

When the water component of the Yield-SAFE model was turned on and assuming a soil depth of 1.5 m, the model predicted substantial reductions in the tree and stand volumes for both the forestry and agroforestry treatments. Both Vézénobres and Silsoe are in areas of relatively low rainfall, and drought stress is known to constrain tree growth at both sites. The predicted tree volumes for a

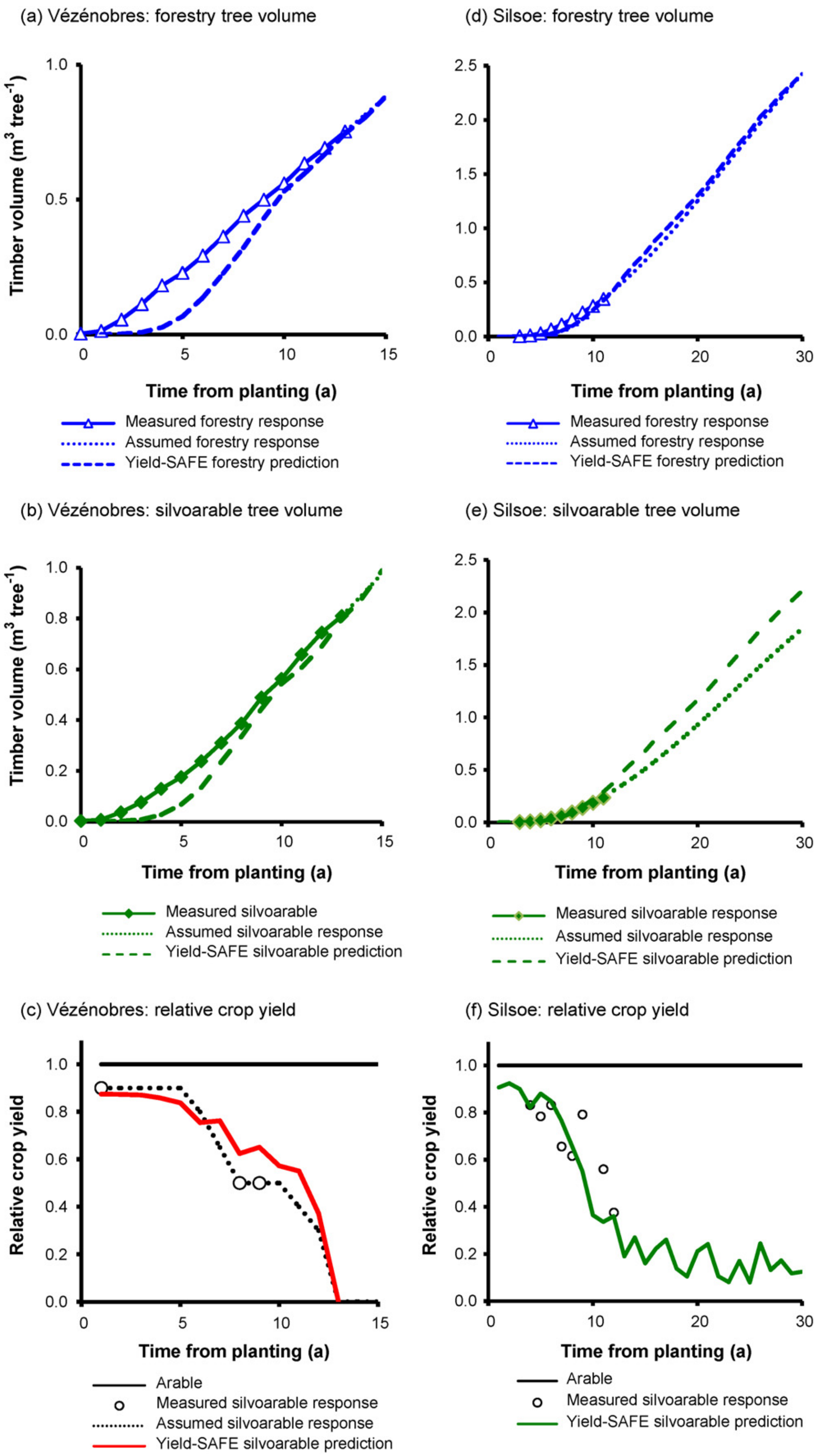

Fig. 4. Comparison of predicted and measured timber yields at (a and b) Vézénobres, (d and e) Silsoe, and relative crop yields at (c) Vézénobres and (f) Silsoe.

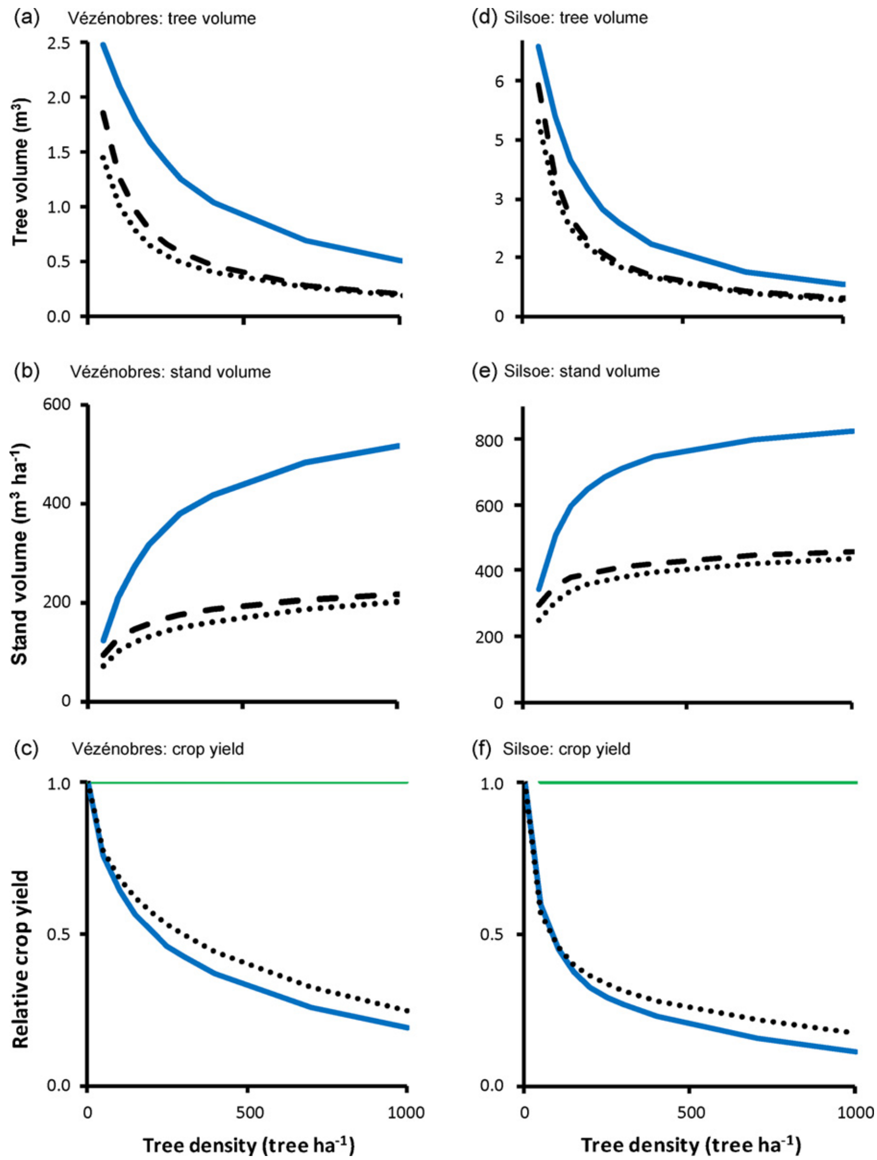

Fig. 5. The effect of tree density and the incorporation of the drought-stress model within the Yield-SAFE model on the (a) tree volume, (b) stand volume and (c) mean relative crop yield at Vézénobres over 15 years assuming a 1.5 m soil depth, and on the (d) tree volume, (e) stand volume and (f) mean relative crop yield at Silsoe over 30 years assuming a 1.5 m soil depth. The treatments are forestry and agroforestry with no water stress (—), forestry with water stress (– – –) and agroforestry with water stress (- - - - - -).

given density was less for the agroforestry than the forestry system because of the competition from the understorey crop for water.

The relative tree yield reduction due to drought stress (assuming a soil depth of 1.5 m) was greater at the Vézénobres site (15 years rotation), than at Silsoe (30 years rotation). The increased sensitivity of the trees at the Vézénobres site could be a result of the period of tree establishment (when a tree–crop is particularly sensitive to water competition) forming a proportionately greater part of the tree rotation. It could also be a result of the lack of summer rainfall in Southern France when competition for water by the crops and the trees is most acute.

The mean relative crop yield over the length of the tree rotation declined with tree density (Fig. 5c and f) because of the reduced planting area, and light and water competition. At both sites, when the water component of the Yield-SAFE model was turned on, the relative yield of the crop component was greater than that when the water component was turned-off. This is because under the water-limiting conditions, tree growth is reduced (Fig. 5 a, b, d and e) and hence there is greater resource availability for the understorey crop.

3.2.2. Response to soil depth

As would be expected, the Yield-SAFE model showed that trees and stand volume for a given stand density decreased as the soil depth became more shallow (Fig. 6a, b, d and e). The trees at Vézénobres were more sensitive to soil depth than those at Silsoe, probably because of the greater importance of the soil being able to store winter rainfall into the summer. The crop yields within the agroforestry system were also sensitive to the soil depth (Fig. 6c and d). However the effect of soil depth became less critical as the tree density increased. It is assumed that this was because the additional water available in a deeper soil was increasingly used by the tree component of the system.

3.2.3. Relationship between tree yields and crop yields

The model was also used to determine the relationship between mean tree yields, crop yields, and soil depth. For both sites, the relationship between tree yield and crop yield was curvilinear (Fig. 7) because the capture of solar radiation and water increased from integrating tree and crop production. Increasing the soil depth also

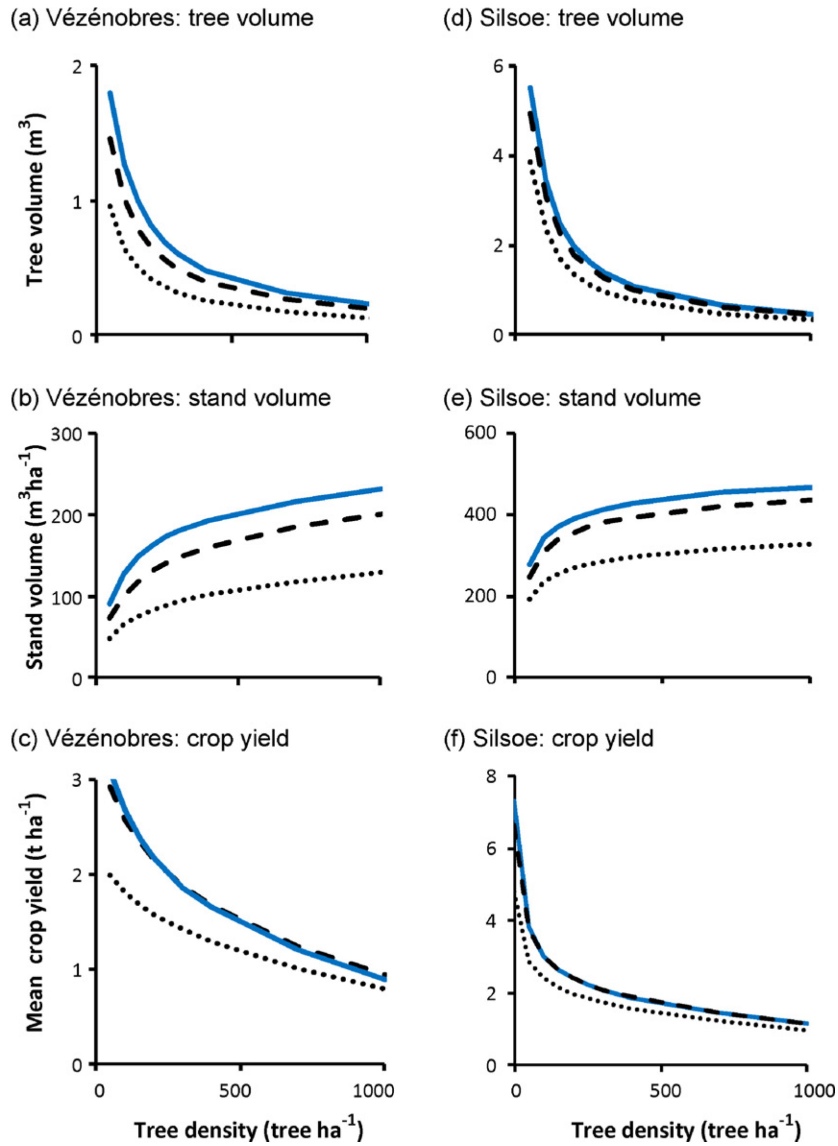

Fig. 6. The effect of soil depth and tree density within the Yield-SAFE model on the (a) tree volume, (b) stand volume and (c) relative crop yield at Vézénobres after 15 years, and on the (d) tree volume, (e) stand volume and (f) relative crop yield at Silsoe after 30 years. The soil depths are 0.5 (- - - - - -), 1.5 (– – –), and 2.5 m (—).

increased the production boundary for each system, as this also allowed the trees and crops to capture more water. As described earlier, the sensitivity of tree and crop production to soil depth seemed to be greater at Vézénobres than at Silsoe. The curves also indicate that the greatest improvement in resource use by integrating tree and crop production tends to occur within the forestry system, probably because a crop can most effectively increase resource capture in the initial years of a forestry rotation before a full tree canopy is achieved. By contrast within the crop dominated systems, adding an additional tree tends to lead to an equivalent linear loss in crop yield.

3.3. Sensitivity analysis

The sensitivity analysis showed that the absolute value of most parameter sensitivities was less than 0.05 indicating relatively small effects on the LER of the silvoarable systems (Table 6). Of those dominant parameters showing sensitivities larger than 0.05, most were tree parameters (i.e. the light extinction coefficient (k_t), the light use efficiency of the tree (ε_t), the initial number of shoots per tree $(N_t)_0$, the maximum leaf area per shoot (A_m), and the critical value at which transpiration starts to be reduced $(pF_{crit})_t$), whilst only one (the light use efficiency (ε_c)), was associated with crop and only for Silsoe.

4. Discussion

As noted previously, this paper aims to demonstrate the applicability of the Yield-SAFE model to: (i) describe existing systems at two contrasting sites and (ii) predict the responses of trees and crops in novel arable, forestry and agroforestry systems. These are discussed below.

4.1. Applicability of the model to describe existing systems

A key concept behind the Yield-SAFE model was to minimise the number of modelled parameters, whilst being able to model tree and crop growth within arable, forestry and agroforestry systems. The parameterisation and calibration process comprised of two phases: parameterisation of the monoculture forestry and arable systems for “potential” tree and crop yields in the absence of drought stress, and then calibration for “actual”

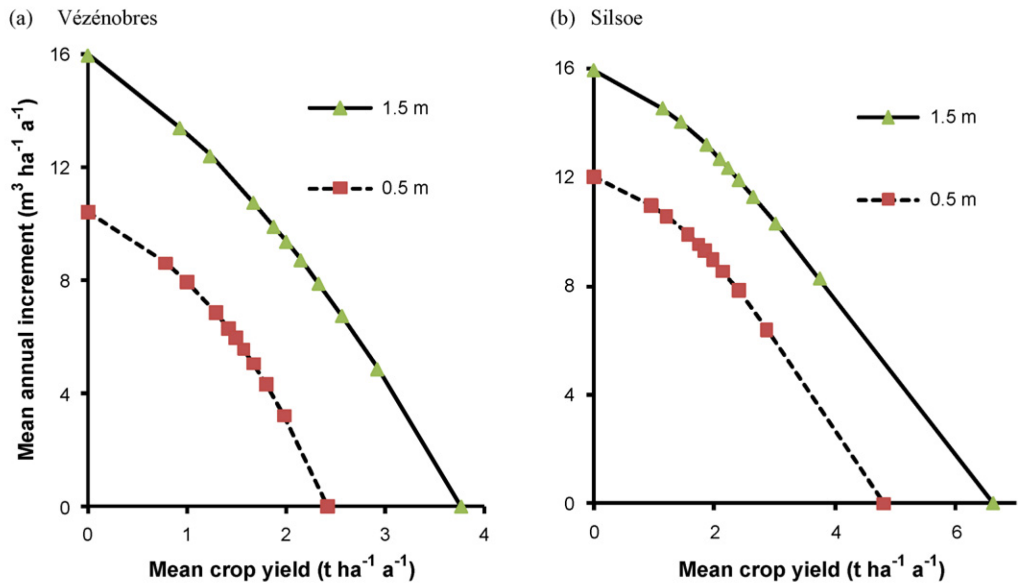

Fig. 7. The modelled interaction between the mean annual increment of the tree component and the mean crop yield of the crop component for (a) Vézénobres and (b) Silsoe for two soil depths.

monoculture tree and crop systems assuming potential water constraints.

Through the calibration process, the mean "actual" yield of the modelled monoculture crop was fixed to equal a measured or reference yield at each site. However inter-annual variability of the climate meant that the actual yield in a particular year varied around that mean. At Silsoe, where the assumed soil depth was 1.5 m, the modelled crop yield was closely linked to the seasonal rainfall (Fig. 3). Because the inter-annual variation in solar radiation and thermal time was relatively small, the inter-annual variation in crop yields due to radiation and temperature were also relatively small.

After appropriate calibration of the monoculture situation, the Yield-SAFE model gave descriptions of the growth and yield of trees and crops in the silvoarable systems that were similar to those measured at the two contrasting sites (Fig. 4a, b, d, and e). At each site the model predicted that crop yields steadily reduced as the trees grew and captured greater amounts of solar radiation and available water in the soil. Increasing tree densities in the silvoarable systems increased the capture of light and water by trees, to the detriment of the crop. These observations indicate that Yield-SAFE can provide credible estimates of the biomass yields and partitioning between crops and trees in silvoarable systems in a range of climate and soil conditions, and for a range of tree and crop species. The Yield-SAFE model was also able to predict long-term changes between the relative growth of trees in forestry and agroforestry systems at both sites. Thus, the growth per tree in the silvoarable system at Vézénobres (0.99 m^3 $tree^{-1}$ at 139 trees ha^{-1}) eventually exceeded that in the forestry system (0.88 m^3 $tree^{-1}$ at 204 trees ha^{-1}) (Fig. 4a and b), whilst in contrast at Silsoe, the growth in the silvoarable systems (2.20 m^3 $tree^{-1}$ at 156 trees ha^{-1}) was lower than that in the forestry system (2.43 m^3 $tree^{-1}$ at 156 trees ha^{-1}) (Fig. 4d and e).

4.2. Responses to tree planting density

The Yield-SAFE model predicted that timber production *per hectare* increased as tree density increased, and that timber production *per tree* decreased as tree density increased because the available solar radiation and water resources were partitioned amongst fewer trees. This can have beneficial economic impacts, as in many countries, the value of timber of equivalent volume increases as tree size increases. Unfortunately the authors have been unable to find published data describing the relative growth of poplar trees at very low tree densities which would indicate if the increased timber volumes predicted by Yield-SAFE at low densities are "reasonable". Therefore one recommendation is the need for further literature searching and/or experimental work to determine the growth of freely grown trees of species commonly grown in forestry and agroforestry systems.

The model was also used to predict the tree yield and crop yield profiles for different tree densities. Such an analysis can be useful in comparing the effect of tree density on profitability and feasibility (Graves et al., 2007), or selected environmental impacts (Palma et al., 2007a,b).

4.3. Relationship between tree and crop yields

In each of the silvoarable systems, tree and crop yields were individually lower on a per hectare system basis than the crop yields in the arable system and the tree yields in forestry (Fig. 6). However the combined levels of production, for example in terms of biomass production, were higher when the trees and crops were grown together rather than as separate systems (Fig. 7).

As noted previously, it has been common practice in agroforestry and intercropping studies to consider yield benefits in terms of the land equivalent ratio (LER) (Mead and Willey, 1980; Ong, 1996; Dupraz, 1998). In practice the calculated ratio is heavily influenced by the assumed sole-cropping regime. If the sole-cropping regime is sub-optimal for maximising the yield component being considered, then it can artificially inflate the LER of the agroforestry system. The ability to investigate a range of tree densities using a model means that it can be possible to identify higher tree density "control" treatments for the calculation of the denominator for the tree component of the LER, compared to the data available experimentally. Hence the maximum LER ratio suggested by Fig. 7 of about 1.12 is less than that previously suggested for the poplar-arable cropping system of 1.22–1.45 by Graves et al. (2007).

4.4. Sensitivity analysis

Most of the dominant tree parameters (i.e. k_t, ε_t, $(N_t)_0$, A_m) had negative normalized sensitivities in that an increase of the param-

Table 6
Tree and crop yields and the land equivalent ratios (LER) for silvoarable systems in Vézénobres and Silsoe with a ±10% change in the nominal value of selected parameters.

	Nominal tree parameters	Monoculture		Silvoarable		LER	Elasticity: $(\Delta LER/LER)/(\Delta pi/pi)$
		Tree yield ($m^3 ha^{-1}$)	Crop yield ($t ha^{-1}$)	Tree yield ($m^3 ha^{-1}$)	Crop yield ($t ha^{-1}$)		
Vézénobres							
Base scenario		180	60	137	37	1.37	
Tree parameters							
k_t	0.8	155	60	116	39	1.39	−0.12
		198	60	155	35	1.35	
ε_t	1.1877	162	60	122	38	1.39	−0.11
		194	60	150	35	1.36	
$(N_t)_0$	1.7938	166	60	126	38	1.38	−0.09
		191	60	147	36	1.36	
N_m	10000	178	60	135	37	1.37	0.00
		181	60	139	36	1.37	
A_m	0.025	164	60	124	38	1.38	−0.09
		193	60	149	35	1.36	
γ_t	0.44	194	60	148	37	1.37	−0.02
		168	60	128	36	1.37	
$(pF_{crit})_t$	4	176	60	129	37	1.35	0.10
		174	60	134	36	1.38	
HI	0.543	162	60	124	37	1.37	0.00
		198	60	151	37	1.37	
Crop parameters							
ε_c	1.34	180	50	143	30	1.39	−0.13
		180	69	131	43	1.35	
S_{emerge}	57	180	61	137	37	1.37	0.00
		180	60	138	36	1.37	
S_h	1312	180	55	139	34	1.38	−0.09
		180	64	136	39	1.36	
HI	0.42	180	54	137	33	1.37	0.00
		180	66	137	40	1.37	
γ_c	0.44	180	62	141	37	1.38	−0.07
		180	58	134	36	1.36	
$(pF_{crit})_c$	2.9	180	58	140	35	1.38	−0.08
		180	61	135	37	1.36	
Silsoe							
Base scenario		379	247	335	98	1.28	
Tree parameters							
k_t	0.8	344	247	295	113	1.32	−0.24
		404	247	364	87	1.25	
ε_t	1.4086	355	247	309	108	1.31	−0.18
		398	247	356	90	1.26	
$(N_t)_0$	0.6225	360	247	313	106	1.30	−0.15
		395	247	352	92	1.26	
N_m	10000	377	247	332	99	1.28	−0.01
		381	247	337	97	1.28	
A_m	0.05	358	247	311	107	1.30	−0.16
		396	247	355	91	1.26	
γ_t	0.28	415	247	365	100	1.29	−0.04
		349	247	309	96	1.28	
$(pF_{crit})_t$	4	363	247	277	118	1.24	0.14
		354	247	317	94	1.28	
HI		341	247	301	98	1.28	0.00
		417	247	368	98	1.28	
Crop parameters							
ε_c	1.34	379	239	344	89	1.28	−0.01
		379	253	325	107	1.28	
S_{emerge}	57	379	255	328	107	1.28	−0.02
		379	241	340	92	1.28	
S_h	1312	379	238	336	96	1.29	−0.04
		379	255	334	101	1.27	
HI	0.57	379	222	335	88	1.28	0.00
		379	272	335	108	1.28	
γ_c	0.30	379	272	341	105	1.28	−0.02
		379	226	329	93	1.28	
$(pF_{crit})_c$	2.9	379	239	348	88	1.28	−0.04
		379	252	321	108	1.27	

eter value would lead to a decrease in the LER. Thus, although tree growth increased for larger values of these tree parameters, the negative effect on the crop as a result of increased shading by the tree caused an overall reduction in LER. However, $(pF_{crit})_t$, which is a measure of the critical soil water potential at which the tree starts to experience water stress, showed a positive sensitivity. This means that the effect of an increase of $(pF_{crit})_t$ on increased tree growth was greater than the negative effect on crop growth, therefore increasing the LER of the silvoarable system.

In the case of the dominant crop parameter, an increase in the light use efficiency of the crop (ε_c) led to an increase in the crop yield. However, because this increased competition for water, the reduction in the tree yield was greater than the increase in crop yield, thus resulting in a negative sensitivity result, meaning that LER was reduced. This effect was only dominant in Vézénobres, where the overall LER was also significantly higher than in Silsoe.

The sensitivity results for the dominant tree parameters appear to be consistent with field experience in silvoarable systems, in that crop yields are reduced as the trees capture more resources that would otherwise be available to the crop. The principal exception is the result for $(pF_{crit})_t$, where an increased capacity of the tree to extract water from a dry soil increased LER, because the tree was utilizing water unavailable to the crop. At present the Yield-SAFE model does not consider the root zone in two layers, i.e. a crop and tree root zone and a tree only zone. In future versions of the model, it would be good to include this effect to better simulate the effects on LER for crop species with differing relative root depths. Some crops are likely to be less complementary than others.

5. Conclusions

This paper describes the implementation of a biophysical tree and crop model, including the selection and measurement of sites to calibrate the model, the process of obtaining the input data for the model, and the validation of the model. Only after the results from the model were found to be credible, was the model used to predict the effect of different tree planting densities on tree and crop yields, and lastly to provide predictions of the land equivalent ratio.

Agroforestry systems are an alternative method for increasing tree cover whilst maintaining crop yields. In France and England they may provide a means of establishing trees where they are scarce. However, since experimental data on silvoarable systems are rare in Europe, computer simulations are needed to provide an estimate of tree and crop yields in mixed systems. Once calibrated against reference arable and forestry yields for each site, Yield-SAFE provided reasonable predictions of tree and crop yields in silvoarable systems in accordance with expert opinion and field measurements at sites in France and the UK. The predicted LERs for modelled silvoarable systems were lower than LERs reported for field experiments because of the capacity to consider a greater range of tree densities for the monoculture tree system. However the calculated LERs are still greater than one and they show that more harvestable biomass could be produced by combining trees and crops on the same area of land rather than growing them separately. When used in the way described here, Yield-SAFE is able to provide useful predictions of yields in silvoarable systems, relative to arable and forestry systems, throughout Europe. The model-based approach presented in this paper could potentially be used to help illuminate current debates on how land should be used to meet competing demands for fuel, food, and fibre.

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