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Yield-SAFE: a parameter-sparse process-based dynamic model for predicting resource capture, growth and production in agroforestry systems

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ABSTRACT

1. Silvoarable agroforestry (SAF) is the cultivation of trees and arable crops on the same parcel of land. SAF may contribute to modern diversified land use objectives in Europe, such as enhanced biodiversity and productivity, reduced leaching of nitrogen, protection against flooding and erosion, and attractiveness of the landscape. Long term yield predictions are needed to assess long term economic profitability of SAF.
2. A model for growth, resource sharing and productivity in agroforestry systems was developed to act as a tool in forecasts of yield, economic optimization of farming enterprises, and exploration of policy options for land use in Europe. The model is called Yield-SAFE; from "YIeld Estimator for Long term Design of Silvoarable AgroForestry in Europe". The model was developed with as few equations and parameters as possible to allow model parameterization under constrained availability of data from long term experiments.

3. The model consists of seven state equations expressing the temporal dynamics of: (1) tree biomass; (2) tree leaf area; (3) number of shoots per tree; (4) crop biomass; (5) crop leaf area index; (6) soil water content, and (7) heat sum. The main outputs of the model are the growth dynamics and final yields of trees and crops. Daily inputs are temperature, radiation and precipitation. Planting densities, initial biomasses of tree and crop species, and soil parameters must be specified.
4. A parameterization of Yield-SAFE is generated, using published yield tables for tree growth and output from the comprehensive crop simulation model STICS. Analysis of tree and crop growth data from two poplar agroforestry stands in the United Kingdom demonstrates the validity of the modelling concept and calibration philosophy of Yield-SAFE. A sensitivity analysis is presented to elucidate which biological parameters most influence short and long term productivity and land equivalent ratio.
5. The conceptual model, elaborated in Yield-SAFE, in combination with the outlined procedure for model calibration, offers a valid tool for exploratory land use studies.

Keywords: Agroforestry model, competition, parameter estimation, resource use, land use, land equivalent ratio, long term yield prediction

INTRODUCTION

Silvoarable agroforestry is the mixed cultivation of arable crops and trees on a single parcel of land. Interest in the introduction of trees in arable systems in Europe is increasing to diversify the farm landscape, promote biodiversity, enhance productivity, and benefit from the function of trees as windbreaks or as protection against nitrogen leaching, flooding and erosion. In recent years, European agricultural policy has sought to reduce arable surpluses and increase the number of trees planted on farms (Burgess et al., 2000). Unlike monoculture forestry, silvoarable agroforestry can provide an annual income. This is obtained from an arable intercrop which is grown for the initial or full duration of the tree rotation, depending in part on the tree density. In tropical countries, there are economic benefits from timber and non-timber tree products on arable land and the production of annual intercrops in plots planted with trees (Graves et al., 2004). Such diversification contributes to economic resilience to external fluctuations in markets. When the tree and crop component in their respource use, for instance, when the trees use a resource, such as water in deeper soil layers, that is not accessible to the crop (Droppelmann et al., 2000), the productivity in agroforestry can exceed the productivity in equivalent areas of arable or forestry monocultures. Complementarity may also exist when tree stands are young and do not capture all the available light. Complementarity lays a basis for higher economic returns.

To express the benefits of mixed cropping systems various characteristics have been proposed (Vandermeer, 1989). In the current analysis a choice has been made for the use of the Land Equivalent Ratio LER), first proposed by Mead and Willey (1980). LER is defined as: ratio of the area needed under sole cropping to the area of intercropping at the *same* management level to obtain a particular yield. LER is calculated as the sum of the fractions of the yields of the intercrops relative to their sole crop yields:

$$LER = \frac{I_1}{M_1} + \frac{I_2}{M_2} + ... + \frac{I_n}{M_n} \quad [1]$$

where
I is the yield of crop when intercropped; *M* is the yield of crop as a monoculture; 1 is one crop; 2 is another crop; *n* is the n^{th} crop.

In agroforestry systems, which are characterized by differences in growing period of the component plant species of the mixture, many approaches are possible to calculate an integrated value of LER over multi-year periods. In this paper we calculate LER in two ways. The first method integrates productivity over the whole rotation, calculating LER as the sum of (1) average value of relative crop yield, compared to monocrop crop yields, and (2) cumulative timber production compared to the monoculture (Equation 2):

$$\mathrm{LER_{rotation}} = \mathrm{Average}\left(\frac{\text{Silvoarable crop yield}}{\text{Monoculture crop yield}}\right) + \frac{\text{Silvoarable timber volume}}{\text{Monoculture timber volume}} \quad [2]$$

The second method of calculating LER produces an estimate for each year *i* in the tree rotation. This estimate is calculated as the sum of (1) the relative crop yield in year *i* (compared with monocrop crop yield in the same year) and (2) cumulative timber production from year 1 through *i* (compared with monoculture tree growth from year 1 through *i*) (Equation 3).

$$\mathrm{LER}_i = \frac{\text{Silvoarable crop yield}_i}{\text{Monoculture crop yield}_i} + \frac{\text{Silvoarable timber volume}_i}{\text{Monoculture timber volume}_i} \quad [3]$$

Thus, LER_i of Equation 3 integrates the relative crop yield in agroforestry in a single year *i* with the timber volume, accumulated from the start of the agroforestry stand until year *i*, standardized against the timber volume accumulated in monoculture.

Two of the key factors in determining adoption and maintenance of silvoarable systems are their profitability relative to alternative enterprises and their feasibility, in terms of the use of farm resources (Burgess et al., 2000; Graves et al., 2005b). The profitability of silvoarable systems, relative to pure arable agriculture and forestry, can be determined by comparing their net present value (NPV), calculated from cost-benefit analysis by discounting and aggregating future benefits and costs (Graves et al., 2005a). The feasibility of the system, within a specific farm depends, among others, on the availability of and requirements for labour or finance. Fundamental to both assessments, is the need for biophysical data on yields of crops and trees in silvoarable as well as in arable and forestry systems. As empirical data on silvoarable systems are scarce, an alternative method is necessary to generate long-term time series of yields based on interactions of trees and crops in mixed systems. Such a method is the use of dynamic computer simulations that predict the effect of climate, tree and crop species, soil type and management choices on tree and crop production, economics and the environment.

The need for a minimal modelling approach
Key issues in the analysis of dynamic simulation models are stability, sensitivity of the output to parameter values, uncertainty propagation and identifiability.

Identifiability analysis attempts to answer the question: can we estimate a unique value for specific parameter, given sufficient data? In general, identifiability decreases with increasing complexity of a model, because of the potential interactions between parameters. If, for a complex model, poorly identifiable parameters are estimated from experimental data, errors in parameter estimates may become very large. As a consequence, uncertainty in model predictions will become large. Hence, from the viewpoint of restricting uncertainty in model predictions, a minimal modelling approach, allowing estimation of a maximum set of identifiable parameters, is preferred (Young, 1984; Ljung, 1987). The need for a minimal modelling approach is high for agroforestry systems, because of the lack of quantitative long term data on the productivity of those systems.

Currently available biophysical models for agroforestry systems, such as WaNulCAS (Van Noordwijk & Lusiana, 1999) and HyPAR (Mobbs et al. 1999) are highly complex and rich in parameters, and the above-mentioned drawbacks of complex models apply. As an alternative approach, a very parameter sparse, yet process-based model is proposed and presented here. The conceptual and algorithmic simplicity of this model, called YIELD-SAFE[1], allow the application of powerful mathematical methods for parameter estimation, and the analysis of uncertainties in model predictions. The model can be easily adapted to different crops and environmental conditions by adjusting parameter values and input functions (Graves et al., 2007), and its code is compact enough to be included in agro-environmental modelling environments that aim at levels of aggregation above the field level (Rabbinge & van Latesteijn, 1992; van Ittersum & Donatelli, 2001).

The ultimate goal of the YIELD-SAFE model is to predict dynamically site-specific long-term tree and crop yields under competitive conditions on the basis of historical or generated weather data, i.e. solar radiation, temperature and precipitation and relevant soil physical characteristics. Growth of trees and crops can essentially be described as the conversion of primary resources, i.e. light, water and inorganic ions into useful organic material, and can therefore be described in terms of the availability of these resources and their utilization efficiency (Monteith, 1990). The objective of the current version of the model is to describe conditions where availability of plant nutrients is not a limiting factor for crop production, hence light and temperature as yield-determining factors and water as (possible) yield-limiting factor (van Ittersum and Rabbinge, 1997) are taken into account.

The objectives of this paper are:

- To describe and justify the conceptual background and equations of Yield-SAFE;
- To provide the first calibration and validation of Yield-SAFE, using published yield tables for poplar stands and two experimental data sets pertaining to the growth of an agroforestry system with poplars and arable crops at two sites in the United Kingdom.
- To provide a sensitivity analysis of Yield-SAFE.

[1] **YI**eld **E**stimator for **L**ong term **D**esign of **S**ilvoarable **A**gro**F**orestry in **E**urope

MATERIALS & METHODS

Model description

The objective of the YIELD-SAFE model is to describe the dynamics of competitive resource acquisition and the associated growth of the constituent components in an agroforestry stand with the minimum number of equations. Such an equation- and parameter-sparse approach is chosen because it provides the best chance that robust parameter values can be identified from experiments. Dynamic equations for the following state variables were identified as essential:

(1) biomass of tree
(2) leaf area of tree
(3) number of shoots of tree
(4) biomass of crop
(5) leaf area of crop
(6) heat sum
(7) available soil water

Biomasses of tree and crop are used to derive temporally-integrated timber volumes and crop yields. Leaf area of tree and crop are essential because they govern radiation capture, and thus the capacity for dry matter production and the associated water loss through transpiration. The number of shoots per tree is required because it governs the potential leaf area within a given year. By contrast the intra-annual leaf area dynamics (at the time scale of days to months) are primarily governed by the growth of leaf area per shoot. Available soil water is included to account for differential growth conditions across Europe with respect to the degree of water limitation, due to variation in precipitation, soil depth and water holding properties of soils. Finally, heat sum is integrated each season to define phenological development of the crops. Nutrient dynamics are not included, because of lack of information from existing agroforestry trials necessary to determine pertinent parameters. The model can be readily extended to include nutrient dynamics, e.g. by quantifying the minimum nutrient uptake required to produce calculated water-limited yields (cf. van Keulen & Wolf, 1988).

Equations and associated parameters were developed as follows:

Potential tree growth

The potential growth rate of the woody biomass of the tree (B_t) is described as:

$$\frac{\mathrm{d}B_\mathrm{t}}{\mathrm{d}t} = \frac{I \quad f_\mathrm{t}\varepsilon_\mathrm{t}}{\rho} \qquad [4]$$

where B_t is the woody biomass of the tree (g dry matter per tree); I is the global radiation, incoming to the forestry or agroforestry stand (MJ per m^2 per day); f_t is the proportion of incoming radiation (I) intercepted by the trees; ε_t is the radiation use efficiency of the trees (g woody dry matter per MJ intercepted global radiation), and

ρ is the tree density (number of trees per m^2 silvoarable area). The variable t (italicized) is time (d), while the subscript t (in roman type) indicates parameters and variables for the tree.

The fraction of radiation intercepted by the trees in the agroforestry system is calculated as:

$$f_\mathrm{t} = 1 - e^{-k_\mathrm{t} L_\mathrm{t}} \qquad [5]$$

where k_t is the radiation extinction coefficient of the tree leaf canopy; L_t is the leaf area index of the tree stand (m^2 tree leaf area per m^2 silvoarable stand).

Water limited effective tree growth
Under water-limiting conditions, and accounting for biomass losses due to maintenance or attrition such as branch senescence and storm damage, Equation [4] is modified into:

$$\frac{\mathrm{d}B_\mathrm{t}}{\mathrm{d}t} = \frac{I\ f_\mathrm{t} \varepsilon_\mathrm{t} w_\mathrm{t}}{\rho} - aB_\mathrm{t} \qquad [6]$$

where w_t expresses the relative effect of soil water potential on the tree growth rate and a is the relative rate of biomass loss due to maintenance and attrition. The factor w_t is calculated as:

$$\begin{cases} \mathrm{pF} \le \mathrm{pF_c}: & w_\mathrm{t} = 1 \\ \mathrm{pF_c} < \mathrm{pF} \le \mathrm{pF_{PWP}}: & w_\mathrm{t} = \dfrac{\mathrm{pF_{PWP}} - \mathrm{pF}}{\mathrm{pF_{PWP}} - \mathrm{pF_c}} \\ \mathrm{pF} > \mathrm{pF_{PWP}}: & w_\mathrm{t} = 0 \end{cases} \qquad [7]$$

where pF is the soil water tension, defined as the negative log of the water potential in cm water. Hence as long as pF is below the critical value ($\mathrm{pF_c}$), there is no reduction, when pF is between the critical value and the permanent wilting point ($\mathrm{pF_{PWP}}$), the degree of reduction is proportional to the difference between current pF and $\mathrm{pF_{PWP}}$ as scaled by the difference between $\mathrm{pF_c}$ and $\mathrm{pF_{PWP}}$, while the reduction is 100% when pF is greater than $\mathrm{pF_{PWP}}$ (Fig. 1).

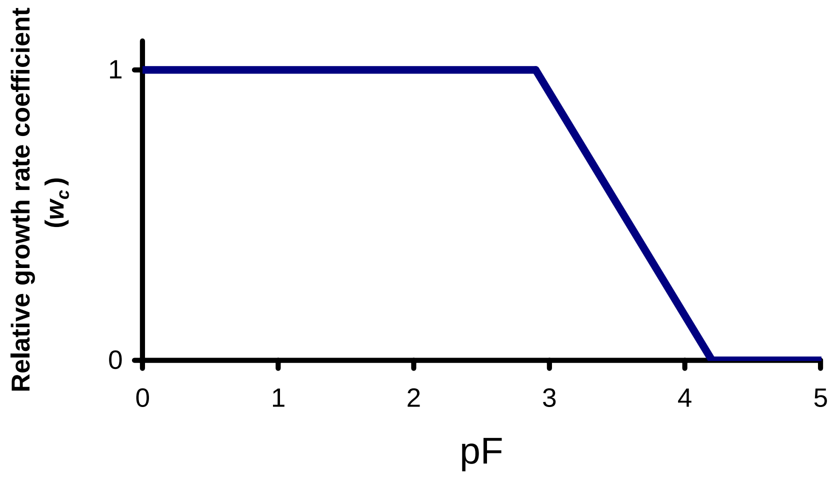

Figure 1 Relationship between the reduction factor for the rate of crop growth (w_c) and the pF of the soil (pF_c = 2.9 and pF_{PWP} = 4.2).

The product term aB_t ensures that in due course, the growth rate of the tree will slow down until, ultimately, the tree will reach a maximum biomass of:

$$B^* = \frac{f_t \varepsilon_t w_t}{a\rho}\tilde{I}$$

where $\tilde{I}$ is a long term average for the incoming radiation. The numerical value of a is very low (in the order of 0.0001 d^{-1} or less; see below), indicating minimal losses and allowing trees to accumulate weight for many decades before reaching equilibrium between growth and loss. Outside the growing season, the rate of change of tree biomass is set to 0.

Water use by the tree

The amount of water that is used by the trees per unit area per day is calculated by multiplying the water-limited growth rate per tree with the tree density (ρ) and a transpiration coefficient, γ_t :

$$W_t = \gamma_t \rho \frac{dB_t}{dt} \qquad [8]$$

where W_t is the tree water use (m^3 water per m^2 silvoarable area per day); γ_t is the transpiration coefficient of the trees (m^3 water per g woody dry matter)

Leaf area of the tree

The rate of increase in leaf area index of a tree leaf canopy (L_t) is calculated as:

$$\frac{dL_t}{dt} = \rho N \frac{A_m - A}{\tau} \qquad [9]$$

where L_t is the leaf area index of the tree (m^2 tree leaf area per m^2 silvoarable area); ρ is the density of trees (number of trees per m^2 silvoarable area); N is the number of shoots on a single tree (see below); A_m is the maximum leaf area per shoot on a tree (m^2); A is the current leaf area per shoot on a tree (m^2; see below); τ is the time constant of the leaf unfolding process (day) as driven by re-allocation of reserve carbohydrates in the spring (Versteeg and van Keulen, 1986)

The rationale for Equation 9 is that early leaf growth in trees is not an autonomous positive feedback process as in crop plants, governed by incident radiation interception, but a translocation and conversion process from reserve carbohydrates, stored at the end of the preceding season, to new leaf biomass. Hence, the dynamics are fundamentally different. The state variable N, the number of shoots on a tree, expresses the “memory” of the tree with respect to preceding year’s number of branches and storage of reserve carbohydrates. Leaves start to unfold at time t_b, the date of bud burst and all leaf canopy is shed at the day of leaf fall (t_f).

Number of shoots per tree

The number of shoots per tree is calculated on the basis of a saturating curvilinear Monod function of tree biomass, according to:

$$N = N_m \frac{B_t}{B_t + K_N} \qquad [10]$$

where N_m is the maximum number of shoots on a mature tree; K_N is the biomass of a single tree at which the number of shoots is half the maximum. As K_N is difficult to estimate from data, an expression for the growth of N was derived from which the parameter K_N is eliminated.

From Equation 10 we derive:

$$K_N = B_t \frac{N_m - N}{N} \qquad [11]$$

After differentiation of Equation [10] and substitution of Equation [11] one obtains:

$$\frac{dN}{dt} = \frac{dB_t}{dt} \frac{N}{B_t} \left(1 - \frac{N}{N_m}\right) \qquad [12]$$

with unknown initial condition $N(t_0)$ where t_0 is the planting date of the trees. In practice, $N(t_0)$ is easier to estimate from experimental data than K_N, hence this reformulation of the model. Furthermore, Equation 12 allows a straightforward adjustment of the tree growth in case of pruning.

Pruning and thinning

When pruning takes place, biomass and number of shoots are reduced by appropriate factors π_B and π_N, which can, in principle, be different. Thinning is effectuated by reducing tree density ρ by a thinning factor π_ρ.

Potential crop growth
Within each cropping season, crop biomass starts at an initial value of $B_c(t_e)$ where t_e is the date of crop emergence. The subsequent potential growth rate of the crop is described as:

$$\frac{dB_c}{dt} = I_c f_c \varepsilon_c \qquad [13]$$

where B_c is the above-ground biomass of the crop (g dry matter per m^2 silvoarable area); I_c is the radiation available to the crop (MJ per m^2 silvoarable area); f_c is the proportion of I_c intercepted by the crop; ε_c is the radiation use efficiency of the crop (g above-ground dry matter per MJ intercepted global radiation)

The radiation available to the crop is calculated as:

$$I_c = (1 - f_t) I \qquad [14]$$

where f_t is the proportion of incoming global radiation intercepted by the tree crowns and I is global radiation, incoming to the agroforestry stand (MJ per m^2 per day)

The fraction of radiation intercepted by the crop (f_c) is calculated as:

$$f_c = C\left(1 - e^{-k_c \frac{L_c}{C}}\right) \qquad [15]$$

where C is the proportion of the total area that is cropped (m^2 cropped area per m^2 silvoarable area); k_c is the radiation extinction coefficient of the crop; L_c is the leaf area index of the crop (m^2 crop leaf area per silvoarable area)

Water-limited crop growth
Under water limiting conditions, Equation [13] is modified into:

$$\frac{dB_c}{dt} = I_c f_c \varepsilon_c w_c \qquad [16]$$

where w_c expresses the reduction in crop growth rate, relative to the potential growth rate. This is calculated in the same way as the value for w_t (Equation 7, Figure 1), but with crop specific parameter values for pF_c and $pF_{PWP.}$

Water use by the crop
Water use by the crop is calculated by multiplying the water-limited growth rate by a transpiration coefficient, γ_c :

$$W_c = \gamma_c \frac{dB_c}{dt} \qquad [17]$$

where W_c is the crop water uptake (m^3 water per m^2 silvoarable area per day)
γ_c is the transpiration coefficient of the crop (m^3 water per g above-ground dry matter. The value of γ_c can vary with crop species or variety, wind speed and the

water vapour pressure deficit of air (VPD) (Loomis & Connor, 1992), but otherwise the value is relatively constant (Monteith, 1990).

Leaf area of the crop

Change in leaf area index of the crop (L_c ; m^2) is calculated as:

$$\frac{\mathrm{d}L_c}{\mathrm{d}t} = \sigma P \frac{\mathrm{d}B_c}{\mathrm{d}t} \qquad [18]$$

where σ is the specific leaf area of the crop (m^2 leaf area per g leaf dry matter), and P is the partitioning coefficient to leaves for the crop; i.e. the proportion of the daily increase in above-ground dry matter that is invested in growth of new leaves. Leaf area starts at an initial value of $L_c(t_e)$ where t_e is the date of emergence. Leaf area growth is set to zero when the heat sum at harvest (S_h) is attained (see below).

Heat sum

The increase in cumulative temperature (heat sum) is calculated as:

$$\frac{\mathrm{d}S}{\mathrm{d}t} = \max\left[0, T - T_b\right] \qquad [19]$$

where S is the heat sum since crop emergence (°C d); T is daily average temperature (°C); T_b is the base temperature for phenological development (°C); the function max [ ] takes the maximum value of the arguments.

Partitioning of dry matter to leaves in the crop

Partitioning of dry matter to leaves decreases linearly with crop development stage, according to:

$$\begin{cases} S \le S_1: & P = P_0 \\ S_1 < S \le S_2: & P = P_0 \dfrac{S_2 - S}{S_2 - S_1} \\ S > S_2: & P = 0 \end{cases} \qquad [20]$$

where P_0 is the proportion of above-ground biomass initially partitioned to leaves; S_1 is heat sum where partitioning of dry matter to leaves starts to decline; S_2 is heat sum where the partitioning coefficient becomes zero.

Soil water dynamics

The model assumes a homogeneous soil of depth D (m) and volumetric water content θ, which is described by:

$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = \frac{1}{D}\left(R + W_{irr} - F_{gw} - W_c - W_t - E_{act}\right) \qquad [21]$$

where θ is soil volumetric moisture content (m^3 per m^3); R is precipitation (m^3 per m^2 silvoarable area per day); W_{irr} is irrigation (m^3 per m^2 silvoarable area per day); F_{gw} is drainage of soil water below the potential rooting zone (m^3 per m^2 silvoarable area per day); E_{act} is actual soil evaporation (m^3 per m^2 silvoarable area per day)

Soil moisture characteristics are often described in terms of soil moisture tension, ψ, i.e. the force with which the soil matrix holds the water. For ease of notation, the tension is then expressed in terms of pF, where pF = $\log_{10}(\psi)$, with ψ is expressed in cm water tension. The relation between ψ and θ is given by the van Genuchten (1980) equation:

$$\theta = \theta_{\mathrm{PWP}} + (\theta_s - \theta_{\mathrm{PWP}})\left[\frac{1}{1+(\alpha\psi)^n}\right]^m \qquad [22]$$

where θ_s is soil water content at saturation (m^3 per m^3); θ_{PWP} is soil water content at permanent wilting point (the lower limit of plant-available water in m^3 per m^3); α , m and n are soil-type specific parameters; ψ is soil water tension in cm water.

Precipitation and irrigation are introduced as forcing functions. Drainage flow to groundwater is dependent on the pF of the soil according to:

$$\begin{aligned} &\mathrm{pF} < \mathrm{pF_{FC}}: \quad F_{\mathrm{gw}} = \delta K_{\mathrm{s}} \\ &\mathrm{pF} \geq \mathrm{pF_{FC}}: \quad F_{\mathrm{gw}} = 0 \end{aligned} \qquad [23]$$

where $\mathrm{pF_{FC}}$ is the pF value at field capacity, usually set to 2.3, and K_{s} is soil hydraulic conductivity at saturation (m per day)

The factor δ is given by:

$$\delta = 10^{-\mathrm{pF_{FC}}/\varphi} \qquad [24]$$

where φ is a parameter that scales the relationship between δ and $\mathrm{pF_{FC}}$. A default value of 2 is assumed for φ. If soil water data is available, φ will be estimated between 1 and 4 depending on the water distribution in the soil, which depends on many factors, but especially on soil characteristics.

Evaporation from the soil surface (E_{act}) is calculated as:

$$E_{\mathrm{act}} = \eta I_{\mathrm{s}} w_{\mathrm{s}} \qquad [25]$$

where η is the heat of vaporization (m^3 water per MJ); I_{s} is the radiation incident on the soil (MJ per m^2 per day); w_{s} is a factor accounting for the reduction in soil evaporation due to drying of the soil, and is calculated in the same way as the reduction factor for the tree (Equation 7; Fig. 1)

Radiation incident on the soil (I_{s}) is calculated as:

$$I_{\mathrm{s}} = I\, f_{\mathrm{t}}\left(Cf_{\mathrm{c}} + (1-C)\right) \qquad [26]$$

where f_{t} is the proportion of incoming radiation intercepted by the trees, f_{c} is the radiation interception by the crop as a fraction of the amount of radiation incident on the crop, and C is the proportion of cropped area. The formula combines the contributions of cropped area ($I\,f_t C f_c$) and uncropped area ($I\,f_t(1-C)$) to the total radiation incident on the soil.

Model implementation

The model has been implemented as a set of difference equations on several computer platforms including MatLab (Stappers et al., 2003) and Microsoft© Excel (Burgess et al., 2004b). These references give further implementation details that are omitted here for clarity.

Poplar validation data

Two agroforestry experiments with poplar (*Populus* species) were carried out in the United Kingdom. Full initial details of the experiments are provided by Burgess et al. (2004a), but the key features are summarised here. The cooler and most northerly site is at the Leeds University Farms at Bramham near Tadcaster in West Yorkshire (53°53’ N, 1°15’ W); the warmest site is at Silsoe in Bedfordshire (52°0’ N, 0°26’ W) in eastern England. Soils at the Leeds and Silsoe sites are sandy clay loam over limestone and clay over clay, respectively. At both sites the main experiment covered 2.5 ha and comprised three replicate blocks that included each combination of four poplar hybrids and three or four arable treatments.

Poplars were planted as unrooted sets in spring 1992 at a rectangular spacing of 10 m between tree rows (in a North-South orientation) and 6.4 m between trees within the rows. Part of the alleys between the tree rows were cropped yearly in the middle 8 m (leaving a 2 m uncultivated strip for the tree row), while another part of the alleys was left uncropped and weed free in subsequent years in order to obtain estimates of the yield of poplar in an agroforestry situation compared to a pure poplar stand at the same density. An area of the same field at least 15 m from the trees was used as an arable monocrop area. Starting in 1992, the rotation at Leeds comprised spring barley (*Hordeum vulgare* L.), peas (*Pisum sativum* L.), two crops of winter wheat (*Triticum aestivum* L.), winter barley, spring mustard (*Brassica alba* L.), winter wheat, winter barley, two winter wheat crops, winter barley and winter oilseed rape (*Brassica napus* L.). At Silsoe, following poor crop yields in the initial three years, there were three winter wheat crops followed by winter beans (*Vicia faba* L.), spring wheat, winter wheat, fallow, winter barley and spring beans. Crop management was the same for intercrop and monocrop. The poplar cultivars were Beaupré, Gibecq, Trichobel and Robusta. From 1992 to 2000 the trees were regularly pruned, by removing the lower whorls of branches, in order to maintain a canopy depth equal to about half the tree height (Burgess et al., 2003).

Measurements

From 1992 onwards, the height of each tree in each arable treatment was measured after leaf fall. The diameters of the same trees were measured at breast height (1.3 m above the ground) each winter from 1994 onwards at the Leeds University site at Branham and from 1995 onwards at the Cranfield University site at Silsoe. Timber volume was estimated by first assuming the trunk is a perfect cylinder, with a volume calculated from height and diameter, and then multiplying this calculated volume by a form factor to account for taper of the trunk (Burgess et al., 2004a). The form factor was derived from poplar yield tables, given in Christie (1994).

Each year, grain, bean or pea yield within each poplar-hybrid x arable-treatment plot was determined by harvesting with a plot combine. Corresponding measurements were also taken within the monocropped control area.

Model calibration for poplar and intercrops

For the calibration of Yield-SAFE the following approach was used. First, the potential growth of monoculture stands of tree and crop species were fitted under specific climatic conditions in Europe, using yield tables for trees (e.g. Thomas et al. 1998) and validated model calculations for crops (Brisson *et al.*, 2003). Potential growth is determined foremost by temperature (which drives developmental and phenological processes) and radiation (which drives photosynthesis) but is unaffected by water and nutrients as these are assumed to be non-limiting under the potential growth assumption (van Ittersum & Rabbinge, 1997). Second, given actual monoculture yields of tree and crops as “reference” yields for a specific experimental site the model was fine-tuned by adjusting – within physiologically meaningful bounds - the transpiration coefficient (γ) and harvest index (HI) and by introducing – if necessary – a management factor (between 0 and 1) that reduces the radiation use efficiency (ε). Hence, yield in agroforestry stands is predicted from the resulting model, which is – as described - calibrated to represent site-specific monoculture behaviour of trees and crops as affected by temperature and radiation driven growth potential in combination with site specific limitations due to water and nutrients, soil properties, and the local effects of weeds, pest, diseases and management shortcomings.

The calibration of model parameters for the potential growth of poplar trees was conducted using published yield tables for unthinned poplar (monoculture) stands with 8 x 8 spacing and a site class of 58 (Thomas et al., 1998). Because timber growth is expressed in terms of timber volume, it was necessary to convert the biomass yield into a timber volume. The timber volume of a tree (V_t; m^3 tree^{-1}) was derived from:

$$V_{\mathrm{t}} = \frac{\mathrm{HI}_{\mathrm{timber}} B_{\mathrm{t}}}{\rho_{\mathrm{timber}}} \qquad [27]$$

where $\mathrm{HI}_{\mathrm{timber}}$ is the proportion of the total woody-biomass partitioned to timber, and ρ_{timber} is the density of the timber (g m^{-3}).

On the basis of practical identifiability analysis we decided to estimate the initial number of shoots, $N(t_0)$, and the radiation use efficiency, ε_t. Other parameter values were fixed at biologically plausible parameter values, based on literature (see results). Attempts to estimate additional parameters led to unreliable results and did not improve the fit. A least-squares optimization algorithm was used to estimate both $N(t_0)$ and ε_t.

As the crop data available related to harvested crop yield (Y_c) rather than crop biomass, it was necessary to assume a crop harvest index (HI_c).

$$Y_{\mathrm{c}} = \mathrm{HI}_{\mathrm{c}} B_{\mathrm{c}} \qquad [28]$$

Simulation data from STICS (Brisson et al., 2003), given appropriate parameters for an Atlantic climate was used to provide potential growth curves for winter wheat.

In particular, the following parameters were adjusted: ε_c, S_0 (heat sum after sowing when crop emerges), S_1, S_2, S_h (heat sum at harvest) and harvest index HI_c. Again, a least-squares optimization was performed to identify the parameter values from the data.

Model validation for poplar agroforestry systems

Given the calibrated parameters related to potential growth, in a second step only three parameters: transpiration coefficient (γ_t or γ_c), harvest index (HI_{timber} or HI_c) and a management factor were adjusted to fit actual yields (i.e. locally attained yields; van Ittersum and Rabbinge, 1997) for the monoculture tree and crop systems at a specific site, in our case Silsoe (UK). The model was then used to predict tree and crop growth within a silvoarable system using these site-specific parameters, and these results were compared with experimental data collected over 12 years.

Sensitivity analysis

In this paper the objective of the sensitivity analysis is to investigate how different biophysical parameters influence the land equivalent ratio (LER). The model parameters were analyzed by systematically changing their nominal values by adding ±10%. The nominal values were obtained from the calibration of Yield-SAFE using the procedure described in the previous section. Then, after running the model with the perturbed parameters, the outputs were stored and the sensitivity was calculated from

$$\frac{\Delta y}{\Delta p_i} = \frac{y(p_i + \Delta p_i) - y(p_i - \Delta p_i)}{2\Delta p_i} \qquad [29]$$

where $y(p_i + \Delta p_i)$ and $y(p_i - \Delta p_i)$ denote the simulation model output (e.g. LER) when only the ith parameter is changed up or down by a small amount Δp_i while keeping the other parameters fixed at their nominal value. In order to avoid scale effects the relative sensitivity was calculated and used for analyses. The relative sensitivity or elasticity (e_{LER}), of LER for a specific parameter p_i, with nominal values $\overline{p}_i$ and $\overline{LER}$, is given by

$$e_{LER} = \frac{\Delta LER}{\Delta p_i} \cdot \frac{\overline{p_i}}{\overline{LER}} \qquad [30]$$

This very simple type of sensitivity analysis provided a first indication of those parameters that dominate the output.

RESULTS

Agroforestry experiments with poplar

During the first 12 years, the UK field experiments showed that poplar tree growth was reduced by the presence of arable crops, rather than a bare-fallow, between the rows of poplars (Fig. 2). The effect on timber volume per tree (or equivalently, per hectare) was approximately minus 30% after 12 years of poplar growth, both in Silsoe and in Leeds. Growth in Silsoe was marginally greater than in Leeds but the effect of crop competition on tree growth was similar at the two sites. During the initial nine years, the mean crop yield in the silvoarable system was 94% of the monoculture yield on a cropped area basis, and 75% on a total area basis, after allowing for the 20% of the area that was uncropped (Fig. 3). After the ninth year, relative crop yields started to decline substantially due to the cessation of pruning and the development of large tree canopies. A trend of the resulting LER is provided in Fig. 4, showing initially high values and a decline after nine years. Different ways of calculating LER, give different results. In Fig. 4, LER was calculated according to Equation 3, that is by summing relative tree growth in SAF as shown in Fig. 1, and relative crop growth in SAF (Fig. 2). Initial calculations (results not shown) indicate that an annual LER, calculated as the sum of annual crop yields (normalized by comparison with monoculture) and the annual increment in timber volume (also normalized by comparison with monoculture) maintained stable values of the order 1.3-1.4 for any year in the experimental period.

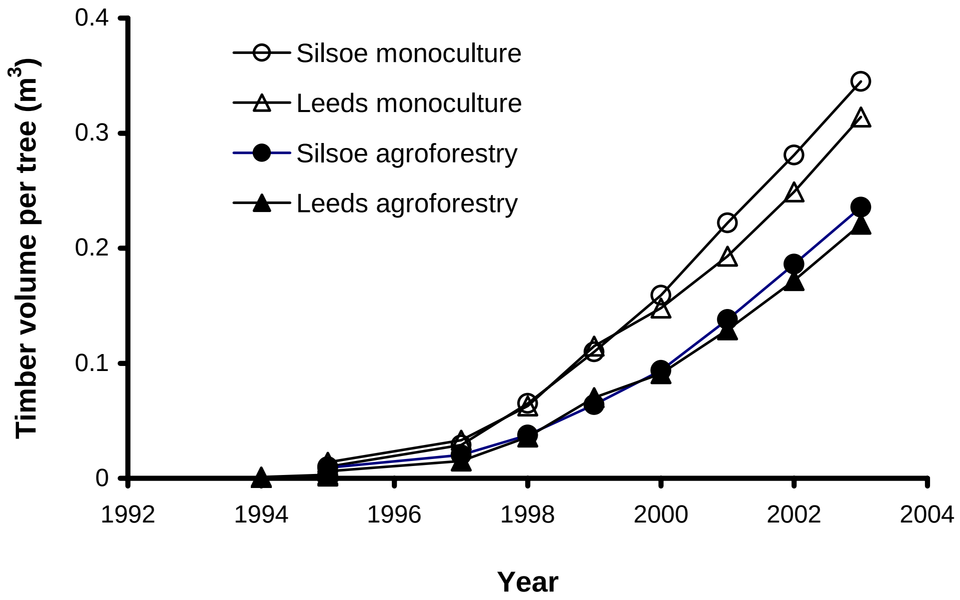

Figure 2 Growth of poplar in agroforestry stand and monoculture Silsoe (UK) and Leeds (UK), 1992-2003.

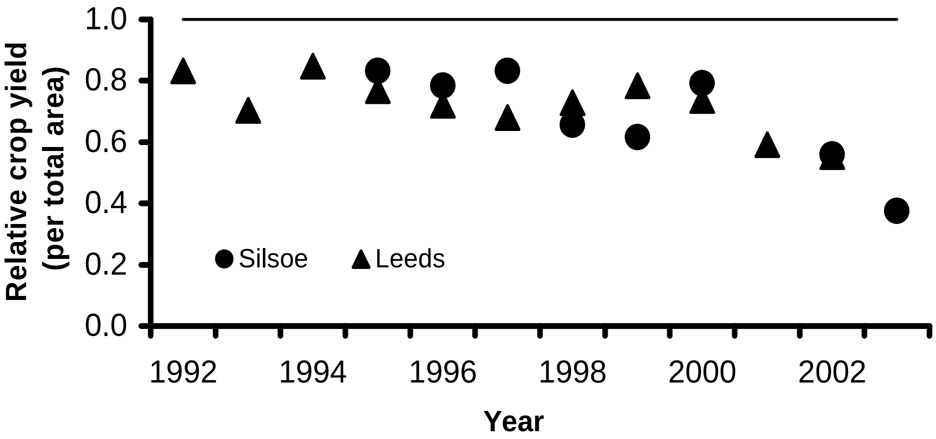

Figure 3 Relative yield of crops in agroforestry stands at Silsoe (UK) and Leeds (UK), 1992-2003. Yield in the intercrop is expressed as a proportion of yield in monocrop.

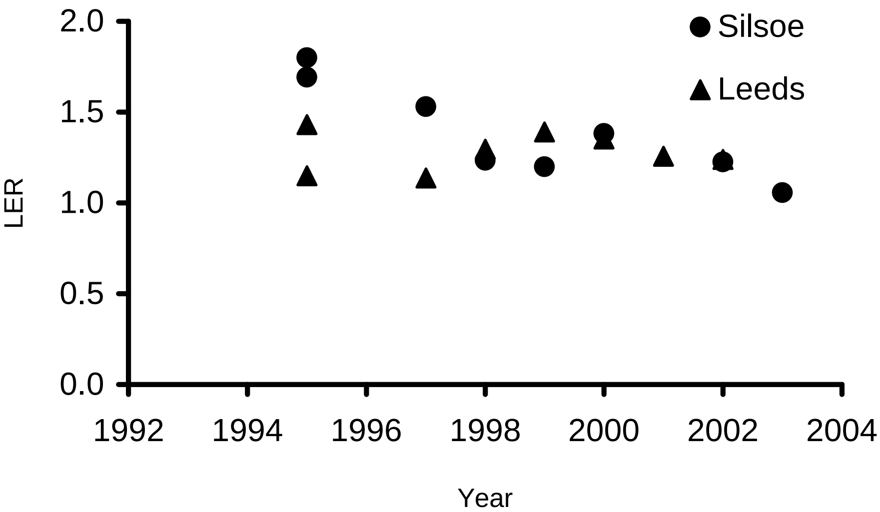

Figure 4 Evolution of the annual land equivalent ratio at Silsoe (UK) and Leeds (UK), 1992-2003. Annual land Equivalent Ratio is calculated as the sum of crop yield in any year and the cumulative tree growth up to the same year, both normalized by their productions in monoculture (Equation 3).

Model calibration

The calibration was made on the basis of the development of timber volume for poplar with a site class of 58, assuming an unthinned stand of 8 m x 8 m (Thomas et al., 1998). Metzger et al (2005) stratified climatic regions in Europe and weather data from Orleans in France was considered to represent the Atlantic conditions which cover north-west Europe, including Great Britain. The dynamic model parameters are described in Table 1, and the estimated model parameters for poplar were ε_t = 1.409 g MJ^{-1} and $N(t_0)$ = 0.6225 The timber volume calculated by the model was similar to that provided by the yield table (Fig. 5)

Table 1 Assumed and estimated tree dynamic model parameters for poplar.

Symbol	Description	Value	Units
Assumed parameters			
ρ_t	Timber density	410000	g m^{-3}
k_t	Light extinction coefficient	0.8	-
ρ	Tree stand density	0.0156	m^{-2}
N_m	Maximum number of shoots per tree	10000	-
A_m	Maximum leaf area per shoot	0.05	m^2
a	Attrition rate of standing tree biomass	0.0001	d^{-1}
τ	Time constant of leaf area growth	10	d
$\mathrm{HI}_{\mathrm{timber}}$	Proportion of woody biomass partitioned to timber	0.5	-
Estimated parameters			
ε_t	Radiation use efficiency	1.409	g MJ^{-1}
$N(t_0)$	Initial number of shoots per tree	0.6225	

Figure 5 Potential poplar growth in the Atlantic region, simulated with Yield-SAFE.

For the potential growth of e.g. winter wheat five parameters were obtained: ε_c = 1.34 g MJ^{-1}; S_0= 57 °Cd; S_1= 456 °Cd; S_2 = 464; S_h = 1312 °Cd and HI_c = 0.51. HI_c was derived directly from the simulation results; the other parameters by calibration. Figure 6 presents the Yield-SAFE prediction of biomass growth in a monoculture wheat crop in Wageningen, using 1983/1984 Wageningen weather data, in comparison with the output from STICS.

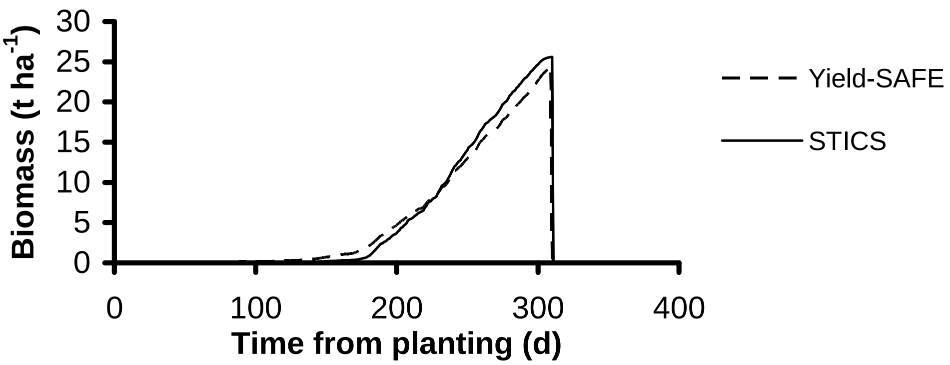

Figure 6 Total crop biomass predictions (wheat) from Yield-SAFE (dashed line) calibrated to outcomes from the comprehensive crop growth model STICS (drawn line). Weather data from Wageningen, 1984.

The next stage was to calibrate the tree and crop components of the Yield-SAFE model for the specific conditions of Silsoe. For the tree component, the model was calibrated by assuming a timber volume per tree at the end of the tree rotation, in this case, of 30 years. At Silsoe, the increase in timber volume during the first 12 years matched that of the yield tables provided by Christie (1994) for an 8 m x 8 m poplar stand with a maximum mean annual increment of 13 m^3 ha^{-1}. Hence from the yield table, a reference timber volume of 2.41 m^3 $tree^{-1}$ was assumed for year 30. Using the Yield-SAFE model, and meteorological and soils data for Silsoe, the values of the transpiration coefficient and the harvest index were modified (Table 2) so that the model predicted a timber yield of 2.41 m^3 $tree^{-1}$ in year 30 (Fig. 7). The tree growth predicted by Yield-SAFE lags somewhat behind during early tree growth; this may partly be due to the assumption of a constant harvest index.

A continuous rotation of winter wheat was assumed for the crop component of the agroforestry system and a reference yield of 8.23 t ha^{-1} was derived from regional farm surveys. To obtain such a mean value over 30 years, it was necessary to modify the transpiration coefficient for the wheat to 0.316 m^2 kg^{-1} (Table 2), which is within the plausible range for temperate conditions. It was not necessary to modify the harvest index. Thus, the model was calibrated to a site-specific reference yield using eco-physiologically meaningful values for all the parameters. This is evidence that the model structure is eco-physiologically appropriate.

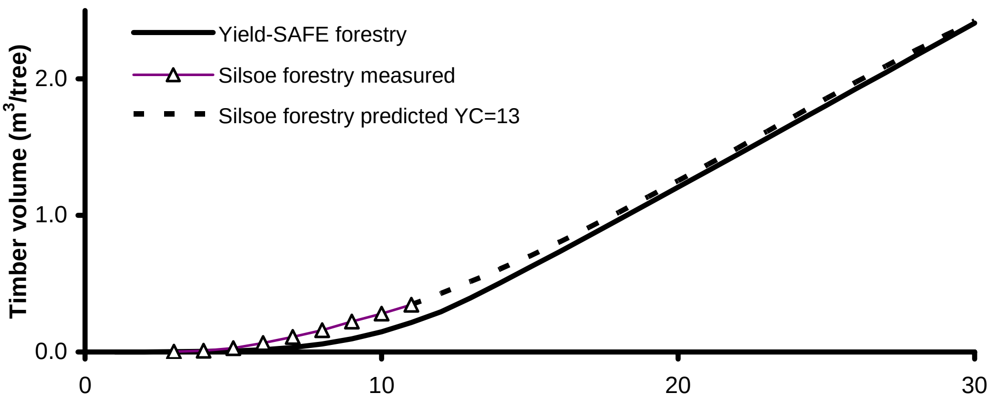

Figure 7 Calibration of Yield-SAFE: Model prediction of tree growth in a poplar agro-forestry stand, compared to yield tables (YC 13; Christie, 1994) and tree growth in the forestry treatment at Silsoe (1992-2003).

Table 2 Reference yields and calibrated values for transpiration coefficient and harvest index for poplar and wheat at Silsoe. The calibrated management factor was 1 for both species.

Species	Time of clear fell (year)	Reference yield at clear fell (m^3 $tree^{-1}$)	Reference crop yield (t ha^{-1} a^{-1}	Calibrated transpiration coefficient (m^3 kg^{-1})	Calibrated harvest index (%)
Poplar	30	2.41	-	0.420	48.6
Wheat	-	-	8.23	0.316	51.0

Model validation

The calibrated model was then run to calculate growth trajectories and yields (under water limitation) for crops and trees within a silvoarable system over a 30 year tree rotation. The predicted relative crop yields for the first twelve years (Fig. 8) generally matched the experimental results. This match between data and simulation results in the agroforestry situation provides further evidence for the validity for the modelling concept and calibration philosophy. Remember that the model was *not* fitted to any data from the agroforestry stand, but only to data from pure stands of crops or trees. Thus, the rather good fit of the model to the yields in an actual agroforestry experiment provides evidence that it correctly captures the essence of the crop-tree interactions.

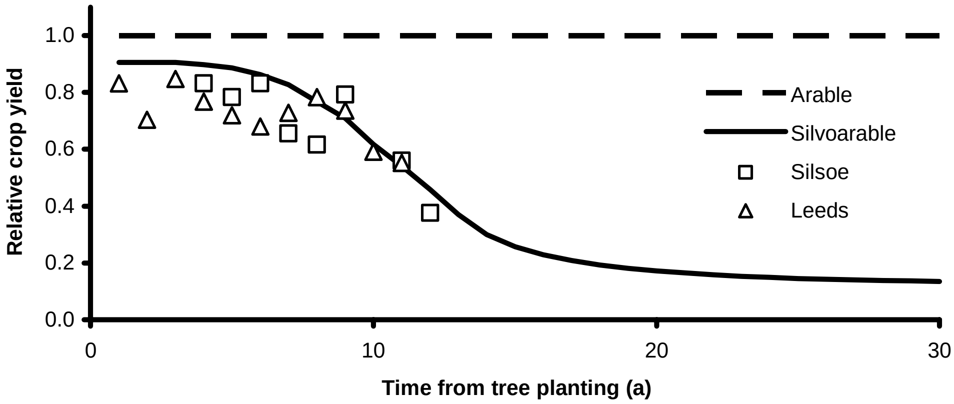

Fig. 8: Validation of Yield-SAFE: model prediction of relative yield of continuous winter wheat, compared with monoculture wheat yield, in a poplar agroforestry stand (156 trees ha^{-1}), compared to observed relative crop yields in Silsoe and Leeds agroforestry experiments, 1992-2004 (open symbols).

Sensitivity analysis

Using the Yield-SAFE model it was possible to predict the LER over a tree rotation of 30 years, using Equation 2. Assuming a continuous rotation of wheat the predicted LER, at the end of the tree rotation of after 30 years, was 1.34. Perturbations of plus or minus 10% in the parameters used for this analysis resulted in values of LER ranging from 1.30 to 1.39 (Table 3). Thus, LER estimates by Yield-SAFE are moderately robust to parameter inaccuracies. The parameters k_t, ε_t, $N(t_0)$ and A_m had the greatest relative effect on LER (cf. Keesman et al., 2005). These tree parameters define to a large extent the shading of the tree on the crop.

A sensitivity analysis (Dennis & Schnabel, 1983) was also undertaken to determine how the elasticity of the LER to specific parameters changed during the tree rotation and with the light extinction coefficient. For this analysis, LER in a specific year was determined using Equation 3. The default parameter sets, with varying values for the tree light extinction coefficient are given in Table 4. The results from both datasets matched the tree and crop growth during the first 12 years of the agroforestry stand, but resulted in a long term overestimation of tree growth, compared to yield tables of Christie (1994). No water limitation was taken into account.

As a result of the different choice of nominal k_t in the two parameter sets, different values are obtained for other parameters, notably those that affect the early growth of the tree: ε_t and the initial number of shoots, $N(t_0)$. The values of ε_t and $N(t_0)$ when k_t

was small (0.4) of 1.84 g MJ^{-1} and 1.32 respectively, were greater than the corresponding values of 1.09 g MJ^{-1} and 1.075 when k_t was large (0.8).

Table 3: The effect of a 10% change in selected parameters in the Yield-SAFE model on the predicted tree and crop yields and land equivalent ratios (LER) for a poplar silvoarable system in year 30.

		Monoculture		Silvoarable			Elasticity
	Nominal value of parameter	Tree yield (m^3 ha^{-1})	Crop yield (t ha^{-1})	Tree yield (m^3 ha^{-1})	Crop yield (t ha^{-1})	LER	ΔLER/LER*p/Δp
Reference		377	247	345	104	1.34	
Tree parameters							
k_t	0.8	334	na	302	120	1.39	
		408	na	377	92	1.30	-0.36
ε_t	1.4086	345	na	316	114	1.38	
		402	na	369	95	1.30	-0.28
A_m	0.05	350	na	319	114	1.37	
		399	na	367	96	1.31	-0.24
$N(t_0)$	0.6225	352	na	321	113	1.37	
		397	na	365	97	1.31	-0.23
γ_t	0.00042	409	na	375	106	1.35	
		350	na	320	102	1.33	-0.08
pF_c	4	369	na	325	110	1.33	
		361	na	332	102	1.33	0.03
N_m	10000	374	na	342	105	1.34	
		379	na	347	103	1.33	-0.02
HI_{timber}	0.486	340	na	311	104	1.34	
		340	na	311	104	1.34	0.00
Crop parameters							
S_h	1312	na	237	345	101	1.34	
		na	262	344	109	1.33	-0.05
pF_c	2.9	na	237	352	95	1.34	
		na	255	339	110	1.33	-0.02
ε_c	1.34	na	233	352	93	1.33	
		na	256	337	114	1.34	0.01
S_0	57	na	247	345	104	1.34	
		na	246	346	103	1.34	0.00
HI_c	0.51	na	222	345	94	1.34	
		na	272	345	114	1.34	0.00
γ_c	0.00032	na	269	349	110	1.34	
		na	228	341	98	1.34	0.00

The LER is calculated with Equation 2. Two lines of model results are presented for each parameter; the top line represents yields and land equivalent ratio for a 10% increase in the parameter, while the bottom line represents consequences of a 10% decrease. The two lines of results are integrated in one value of elasticity. na = not applicable

Table 4: Parameter setting and initial conditions (after calibration) for a sensitivity analysis of Yield-SAFE for a poplar agroforestry stand (156 trees ha^{-1}) with continuous wheat.

Component	Symbol	Unit	Parameter set 1	Parameter set 2
Tree	ε_t	g MJ^{-1}	1.84	1.4086
	k_t	-	0.4	0.8
	A_m	m^2	0.05	0.05
	τ	d	10	10
	a	-	0	0.0001
	$N(t_0)$	tree^{-1}	1.32	0.6225
	$B_t(t_0)$	g tree^{-1}	100	100
	$L_t(t_0)$	m^2 tree^{-1}	0	0
	N_m	tree^{-1}	8000	10000
	t_b	Day of year	100	100
	t_f	Day of year	265	300
Crop	ε_c	g MJ^{-1}	1.6	1.6
	k_c	-	0.7	0.7
	σ	m^2 g^{-1}	0.02	0.02
	P	-	0.8	0.8
	T_0	^{o}C	0	0
	S_0	^{o}C d	150	150
	S_1	^{o}C d	160	160
	S_2	^{o}C d	2350	2350
	S_h	^{o}C d	2950	2950
	$L_c(t_0)$	-	0.1	0.1
	$B_c(t_0)$	g m^{-2}	10	10
	t_s	Day of year	280	280
	t_h	Day of year	235	235

The elasticity analyses show that the most sensitive parameters were associated with the tree component of the model (Table 5). The importance of the tree parameters in determining the complementarity of resource use, as expressed by the value of LER, is also shown in a mathematical analysis by Keesman et al. (2005). Complementarity under potential growing conditions is entirely the result of the tree leaf canopy transmitting light that can be utilized by the crop component in the system. The maximum number of branches of the tree (N_m) has very low elasticity initially, but gains in importance as the trees grow. For mature trees, the maximum amount of shading by trees is determined in part by N_m; hence this parameter influences LER in a mature stand more than in a young stand.

The crop's partitioning coefficient to leaves showed large sensitivity during the early years of the tree rotation. Surprisingly, some crop parameters attained greater relative importance to LER during the late years (20 and 25) of the tree rotation. For instance, in year 25, when the maximum number of shoots is (almost) achieved and the shade is severe and the contribution of crop growth to LER small, the crop parameters light extinction (k_c) coefficient and light use efficiency (ε_c) still become important. This is because, due to the large leaf area of the tree leaf canopy, changing the value of k_t by a factor 0.002 (0.2 %) has only a small effect on the amount of light available for the crop. Given the shade condition, a small change (0.2 %) of the value of P, k_c and ε_c (responsible for light interception and light use efficiency by the crop) has an impact on crop growth and LER. The effect is clearest at the greater nominal value of tree light interception (k_t = 0.8; Table 5).

Table 5. Ranking of elasticities of land equivalent ratios in years 2, 10 and 25 of a poplar-wheat agroforestry stand to biological parameters of tree and crop, for tree parameter scenario's based on an assumed coefficient of light extinction k_t of 0.4 and 0.8.

		Parameter set 1 (k_t = 0.4)			Parameter set 2 (k_t = 0.8)		
Component	Parameter	Year 2	Year 10	Year 25	Year 2	Year 10	Year 25
Tree	t_b	1	1	1	1	2	1
Crop	P	2	8	7	2	8	3
Tree	k_t	3	3	2	3	3	6
Tree	A_m	4	4	3	4	4	5
Tree	$N(t_0)$	5	5	9	5	5	9
Tree	t_f	6	2	5	6	1	7
Tree	$B_t(t_0)$	7	7	11	7	7	11
Tree	ε_t	8	6	10	8	6	10
Tree	τ	9	10	12	9	9	12
Crop	k_c	10	11	6	10	10	2
Crop	ε_c	11	12	8	11	11	4
Crop	S_1	12	16	13	12	14	15
Crop	S_2	13	14	14	13	13	13
Crop	$B_c(t_0)$	14	13	15	14	15	14
Crop	$L_c(t_0)$	15	15	16	15	16	16
Crop	σ	16	17	17	16	17	17
Tree	N_m	17	9	4	17	12	8

Ranking per column, i.e. over all parameters in a given year, with the first rank (1) for the most sensitive parameter.

DISCUSSION

Compared to existing bio-physical agroforestry models (e.g. Mobbs *et al.*, 1999; van Noordwijk & Lusiana, 2000), the model proposed here is very simple. In support of this approach the following arguments can be given: a simpler model is often easier to parameterise and may produce more robust results; it is less work to build; and it is easier to explain and understand. This results in a shorter learning curve when the model is used in upscaling studies, and this may favour its inclusion in higher level studies, e.g. explorations of land use. Of course, a simple model may be underparameterised and unable to represent real situations using the few equations that were chosen as essential. We have not encountered data sets in which this is the case. This model was built with the philosophy that it could be extended when simulation of realistic situations required further detailing. This might be necessary, for instance, when agroforestry at different nutrient levels and nutrient limitation is simulated. However, the current set of parameters can represent many realistic situations without expanding the set of variables or equations, by simply adjusting values of parameters to specific conditions. For instance, the effect of nutrient limitation on growth rates can be captured in the value of the light efficiencies ε_c and ε_t. Our philosophy with Yield-SAFE is that the model should keep its present simple structure until it is unable to represent real situations due to lack of structure or degrees of freedom. In this sense we follow Peters' (1991) plea for simple, useful and predictive models in ecology.

In the current model version, the leaf area of the trees was assumed to spread out over the whole of the agroforested area, without explicitly accounting for clumping of tree leaf area in the tree crowns. Reasoning from existing literature on light distribution in crops (e.g. Goudriaan & van Laar, 1994) indicates that the extinction coefficient might change at low tree densities as the canopy is more heterogeneous. Initial use of the model has suggested that it may be necessary to modify the light extinction coefficient in such situations. An alternative approach is to use detailed models on light distribution (e.g. Pronk et al., 2002) to estimate parameters for Yield-SAFE. Likewise, detailed models for root distribution and activity in agroforestry might be used to parameterize Yield-SAFE functions for water capture by crops and trees.

During the same project an elaborate model was built for agroforestry system performance, based on details of resource use processes in agroforestry systems. This model is called Hi-SAFE to indicate the high level of process detail contained in it. The applications of Hi-SAFE are more geared towards shorter time scales, and detailed questions regarding spatial configuration in agroforestry designs, whereas Yield-SAFE focuses on issues of production and resource use in the longer term. For both models, parameter estimation is an issue. Yield-SAFE requires long term data on tree growth for parameter estimation and validation of model results. Such data are not yet available for agroforestry systems, but they may become available in the future as the experiments that have been planted in the 1990s mature and accumulate timber. It is quite important that minimal data are collected in such experiments to allow estimation of parameters of the model proposed here. In this respect it would be very helpful if records were taken of leaf area index and/or soil cover by the crop as well as the trees at different times during the season. Moreover, allometric relationships for widely-spaced trees are needed. At the present time, for studies on *future* land use, there is a pressing need for models that can be built with the limited information on agroforestry that is now available, as very few agroforestry systems have yet been planted in Europe. A simple model like Yield-SAFE can play a pivotal role in land use explorations by predicting production in agroforestry systems by integrating the vast information on forestry and arable systems, based on well proven eco-physiological principles, that – as this study shows – hold up as well in agroforestry as in agriculture and forestry.

ACKNOWLEDGEMENT

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Appendix A. Variables and parameters in Yield-SAFE

Symbol	Units	Meaning
State variables		
B_t	g tree^{-1}	Dry mass of the trunk and branches of the tree
L_t	m^2 m^{-2}	Leaf area index of trees, i.e. tree leaf area per area silvoarable system
N_t	-	Number of shoots per tree
B_c	g m^{-2}	Above-ground dry mass of the crop per area of the silvoarable system
L_c	m^2 m^{-2}	Leaf area index of crop, i.e. crop leaf area per area of silvoarable system
θ	m^3 m^{-3}	Volumetric water content of the soil
S	°C d	Heat sum since crop emergence
Tree parameters		
ε_t	g MJ^{-1}	Radiation use efficiency of the trees, i.e. woody biomass produced per unit intercepted short-wave radiation
k_t	-	Light extinction coefficient of the trees
γ_t	m^3 g^{-1}	Transpiration coefficient of the trees, i.e. water transpired per unit of woody dry matter produced
A_m	m^2	Maximum leaf area of a single tree shoot
τ	d	Time constant of leaf area growth of a tree shoot
a	d^{-1}	Relative rate of attrition of standing tree biomass
Crop parameters		
ε_c	g MJ^{-1}	Radiation use efficiency of the crop, i.e. above-ground dry biomass production per unit of intercepted total short-wave radiation
k_c	-	Light extinction coefficient of the crop
γ_c	m^3 g^{-1}	Transpiration coefficient of the crop; i.e. water transpired per unit of above-ground crop dry biomass
σ	m^2 g^{-1}	Specific leaf area of crop; i.e. leaf area per mass of dry matter
S_h	°C d	Heat sum at crop harvest
T_b	°C	Base temperature for crop phenological development
P_0	-	Initial partitioning factor to leaves
S_1	°C d	Heat sum at which partitioning to leaves starts to decrease
S_2	°C d	Heat sum at which partitioning to leaves ceases
Soil parameters		
pF_{PWP}	-	Log of soil water tension expressed as cm of water at permanent wilting point
pF_{FC}	-	Log of soil water tension expressed as cm of water at field capacity
m, n	-	Shape parameters of the van Genuchten equation describing the (θ, ψ) function
K_s	m d^{-1}	Soil hydraulic conductivity at field capacity
D	m	Depth of the soil compartment

Appendix A. Variables and parameters in Yield-SAFE (continued)

Symbol	Units	Meaning
Intermediate variables		
P	g g^{-1}	Partitioning coefficient of above-ground dry matter to leaves
I_c	MJ m^{-2}	Radiation underneath the tree leaf canopy per area of silvoarable system
f_c	-	Proportion of radiation incident on crop intercepted by crop
w_c	-	Coefficient (0-1) expressing response of crop growth rate to water shortage
f_t	-	Proportion of incident radiation intercepted by trees
w_t	-	Coefficient (0-1) expressing response of tree growth rate to water shortage
w_s		Coefficient (0-1) expressing response of soil evaporation to water shortage
ψ	cm water	Water tension of soil
pF	-	Water tension of soil using a log scale in pF-units: $\log_{10}(\psi)$
δ	-	Parameter affecting drainage rate below root zone
Physical constants		
η	g MJ^{-1}	1/heat of vaporization
Forcing functions		
I	MJ m^{-2}	Daily total short wave radiation
T	°C	Daily mean temperature
R	m^3 m^{-2}	Daily precipitation
Management functions		
C	m^2 m^{-2}	The cropped area expressed as a proportion of the total silvoarable area
t_s	DOY	Crop sowing date (for each year in the tree cycle)
ρ	trees m^{-2}	Tree stand density
π_t	-	Proportion of trees thinned (time-dependent)
π_b	-	Proportion of tree biomass pruned (time-dependent)
π_s	-	Proportion of tree shoots pruned (time-dependent)
Initial conditions		
$N(t_0)$	$tree^{-1}$	Number of shoots on a newly planted tree

Note: DOY is Day of Year