Modelling agroforestry systems

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Chapter 7

Modelling agroforestry systems

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1 Introduction

Agroforestry can be defined as 'the practice of deliberately integrating woody vegetation (trees or shrubs) with crop and/or animal systems to benefit from the resulting ecological and economic interactions' (Burgess and Rosati, 2018). In the Oxford English Dictionary a 'system' is defined as 'a set of things working together as a mechanism or interconnecting network'. Hence, for the purpose of this chapter we assume that an agroforestry system is an interconnecting network of woody vegetation with crops and/or animals that work together. There are large temporal differences in the growth and development of the woody component in an agroforestry system and the crop and/or animal component. The time frame between planting a tree and it reaching maturity can be 20–100 years whereas an annual crop and some animals can reach maturity in months. Hence the growth periods for the trees and the crops and livestock in agroforestry systems are substantially different. This diversity in the range of time, and also spatial, scales and the typically non-linear ways in which the components interact mean that agroforestry is a 'complex' system (Boulton et al., 2015).

Due to the long time periods involved in tree growth, our understanding of agroforestry systems will be very restricted if it only depended on experimental data. One way to improve our understanding and management of agroforestry systems is to use models. The term 'agroforestry model' has numerous meanings. Using the Scopus Search Engine (https://www.scopus.com), a literature search of peer-reviewed papers between 1990 and 2018 using the term 'agroforestry model' in the title, abstract or keywords identified 56 papers, of which 53 were accessible. Of these, 33 of the papers used the term 'agroforestry model' simply in the sense of a type of agroforestry system. This is not the focus of this chapter. Instead we use the term 'model' in the sense, defined by the Oxford English Dictionary, as 'a simplified description, especially a mathematical one, of a system or process, to assist calculations and predictions'. In the context of this chapter, models are representations of the real world that people have developed with the intention of making life more predictable, effective, efficient and/or enjoyable. Models can be qualitative (see Section 2.6.1), but most of the agroforestry models described in the chapter are quantitative, that is, they are based on numerical relationships.

Models of tree and crop growth are relatively new. Cheap digital computers were not widely available until the 1970s and 1980s, and Huda and Ong reported in 1987 that 'no models are yet available for simulating intercropping and agroforestry systems'. Because of the complexity, agroforestry modelling is also a time-consuming process, and hence a model user or developer is well advised to be clear about the objectives for using or developing a model. Matthews et al. (2000) identified that models were generally used by three types of end users: researchers, decision-makers, and teachers and trainers. Luedeling et al. (2016) have also highlighted five objectives for using models. Two of these relate to research: identifying knowledge gaps and testing interactions through 'virtual experiments'. A third objective relates to the provision of decision support. The final two objectives relate to teaching (and also research) in terms of using models to synthesise existing knowledge and to share that knowledge with others. The important role played by models to synthesise knowledge is also highlighted by Lusiana et al. (2011), who reported that clarity of thinking is often rated higher amongst model users than empirical precision. The use of crop simulation models as a tool in education has been reviewed by Graves et al. (2002).

The objectives of this chapter are as follows: (1) to examine the current state of modelling of agroforestry systems, (2) to give an example of how agroforestry modelling can be used to enhance sustainability, (3) to identify potential future trends and (4) to describe sources of further information.

2 Current state of agroforestry modelling

2.1 Agroforestry models as tools: what is the objective?

Models are tools that have been developed to make research, management or teaching more effective. In a conventional toolbox you may have many tools such as a hammer, a screwdriver and a saw. In a similar way, a wide range of agroforestry modelling tools is available. The most appropriate agroforestry model will depend on the problem to be addressed and, as indicated above, the first step in developing or using a model to examine an agroforestry system is to clearly define your objective. In the same way that you should not use a screwdriver to drive in a nail, or a hammer to remove a screw, using agroforestry models for situations that they were not designed for can cause problems.

A review across temperate and tropical areas suggests that there are six major groups of agroforestry model (Table 1). These are as follows: (1) allometric or regression models, (2) models where tree and crop yields are included as inputs that describe the environmental impacts of agroforestry, (3) plot-scale models where the focus is on tree and/or crop growth, (4) architecture models, (5) farm-scale management decision models and (6) landscape models. Each of these model types are considered in turn, with the greatest focus given to plot-scale models.

Table 1 Peer-reviewed papers describing the use of allometric, non-growth models, plot-scale models of tree and crop growth, architectural models, farm decision models and landscape agroforestry models

Model type	Name or description of agroforestry model	Example reference
Allometric models	Models relating tree height, diameter, and carbon storage	Khaine and Woo (2018); Moussa and Mahamane (2018)
Non-growth models of soil carbon	CO2FIX	Panwar et al. (2017)
	SCUAF (Soil Changes Under AgroForestry) model	Young et al. (1998); Grist et al (1999)[1]; Lojka et al. (2008);
	ICBM/N model	Salazar et al. (2011)
Plot-scale models of tree and crop growth	ALWAYS (Alternative Land-use With AgroforestrY Systems) silvopastoral model	Bergez et al. (1999); Balandier et al. (2003).
	APSim Next Generation	Keating et al. (2003); Holzworth et al. (2014); Luedling et al. (2016); Smethurst et al. (2017); Dilla et al. (2018)
	Coffee agroforestry model	van Oijen et al. (2010)
	Hi-sAFe or STICS[2]	Talbot and Dupraz (2012); Talbot et al. (2014); Artru et al. (2017); Dupraz et al. (2018)
	HyPAR: The “Hybrid” tree model with PARCH crop model	Mobbs et al. (1998); Lawson et al. (1995)
	WalNulCAS	Van Noordwijk and Lusiana (1999); Radersma and Ong (2004); Magcale-Macandog (2014); Coulibaly et al. (2014);
	Yield-SAFE	van der Werf et al. (2007); Keesman et al. (2007); Graves et al. (2007, 2010); Keesman et al. (2011); Talbot et al. (2014); Palma et al. (2018); García de Jalón et al. (2018b)
Architectural models	“AMAP” canopy methodology ARCHIMED coconut model FracRoot root model	De Reffye et al. (1995); Mialet-Serra et al. (2001) Lamanda et al. (2008) Ozier-Lafontaine et al. (1999)
Farm decision models	Conceptual model of farm decisions	Meylan et al. (2013)
	Knowledge based system to identify agroforestry grants	Acuña et al. (1997)
	Model ranking agroforestry threats	Moral et al. (2014)
	BEAM and POPMOD Bio-economic models	Thomas (1991); Willis et al. (1993); Purnamasari et al. (2002);
	ARBUSTRA	Liagre (1997)
	Agroforestry Estate Model	Knowles and Middlemiss (1999)
	Agroforestry Calculator	Agriculture Western Australia and Campbell White and Associated Pty Ltd (2000)
	Farm-SAFE	Graves et al. (2007); Graves et al. (2011); García de Jalón et al. (2018b)
	Forage-SAFE	García de Jalón et al. (2018a)
	Financial model including “real options”	Freya et al (2013)
	Welfare maximisation model	Dhakal et al. (2007)
	Agroforestry adoption models	Lovrić et al. (2018).
Landscape	Landscape models	Jackson et al. (2013); Kay et al. (2018); Zeng et al. (2018)

[1]: Combined with an economic model

[2]: Used to determine the effect of different levels of solar radiation on a barley crop

2.2 Allometric or regression models

Allometry is the study of how the characteristics of a living organism change with size. Allometric relationships are sometimes referred to as 'empirical' models; the Oxford English Dictionary defines empirical as 'based on observation or experience rather than theory or pure logic'. Whilst empirical models are useful for summarising past data and for interpolation (Boote et al., 1996), they typically 'contain no information beyond the original data' (Thornley and Johnson, 1990).

Commercial forestry makes wide use of allometric relationships such as yield tables describing, for example, how tree volume changes with tree height and tree diameter for a specified tree density (Burkhart and Tomé, 2002). For example, in the United Kingdom, there are timber yield data for poplar given at 5-year intervals for a given yield class (Christie, 1994). It is also possible to use these data to construct further polynomial regression models that allow the interpolation of timber yields for the intervening years. Although the coefficients in such polynomial curves have little physiological meaning, there are examples where there is a physiological basis for a regression. For example the cross-sectional area of a tree trunk is a square function of its diameter. van Noordwijk and Mulia (2002) also explain how the fractal nature of some relationships means that it is also possible to develop functional branch analysis models to predict, for example, the weight of branches and leaves, from the stem diameter (van Noordwijk and Mulia, 2002; MacFarlane et al., 2014).

Allometric relationships for agroforestry systems are sometimes reported in scientific papers (e.g. Khaine and Woo, 2018; Moussa and Mahamane, 2018). They are also used in some detailed growth models (Bergez et al., 1999). Even in models that calculate the increase in tree dry matter, allometric models can be used to relate changes in tree dry weights to height, diameter and timber volume.

2.3 Non-plant growth models to determine agroforestry impact

There are a number of agroforestry models that do not calculate plant growth, but can still be used to examine the effect of forestry, agricultural or agroforestry systems on environmental impacts such as changes in soil carbon, soil nutrients or water flow. One example is the Soil Changes under AgroForestry (SCUAF) model (Young et al., 1998) which has an annual time step. The user enters the proportion of the area allocated to trees and agriculture in year one and the growth rate of the trees and crops in each year. The model can then be used to estimate the effects of the trees on changes in soil properties including soil erosion, soil organic matter and nutrients, and also on subsequent rates of plant growth. In a similar way, the CO2FIX model has been used to determine the carbon sequestration of poplar agroforestry systems in India both above and below ground (Panwar et al., 2017). With this model, the user inputs estimates of the annual growth of the trees and the anticipated crop yields.

2.4 Plot-based mechanistic models of tree and crop growth

The most widely cited agroforestry models are those that can be used to predict the effect of tree and crop interactions over time. Sinclair and Seligman (1996) defined a crop model as 'the dynamic simulation of crop growth by numerical integration of constituent processes with the aid of a computer'. Matthews et al. (2000) defined a crop model as 'a computer program describing the growth of a crop in relation to the environment operating on a time-step an order of magnitude below the length of a growing season, and with the capacity to output variables describing the state of the crop at different points in time'.

Most crop and agroforestry models include a 'mechanistic' or 'explanatory' component in that they attempt to describe behaviour at one level by using an understanding of what occurs at a sub-level (Whisler et al., 1986; Thornley and Johnson, 1990). Whisler et al. (1986) argue that it is generally unnecessary to build a crop model using an understanding on what happens at more than two levels of hierarchy lower. For example the growth of a crop can generally be determined by the interception of light by a canopy and the uptake of water by a root system, rather than by explaining what is occurring at a cellular level. The anticipated advantage of developing mechanistic models based on sub-level processes is that it should allow the model to be used in a wider range of contexts, which also makes it useful as a research tool (Table 2). However their ability to match observational data may be no better than an empirical model.

Table 2 A comparison of the principal differences between empirical and mechanistic models (based on Thornley and Johnson, 1990)

Type	Mechanistic or explanatory models	Empirical or correlative models
Scope	Wide	Restricted
How does the model deal with time?	Dynamic	May be static
Connections to observational data	Can be tenuous	Generally good
Accuracy of predictions	Variable	Generally good
Typical use	Research and teaching	Management
Typical complexity	Complex	Simple

Despite the division between mechanistic and empirical models shown in Table 2, in practice there is a continuum between pure mechanistic models and pure empirical models. Boote et al. (1996) argue that most crop simulation models are a 'mixture of empiricism and mechanism', and Whisler et al. (1986) note that all models become empirical at some level. However ideally these empirical relationships occur at a sub-level and, where possible, they are formulated in a way that has a theoretical basis. Another unobserved area in which model use depends on correlation is in the assumption that the climate variables measured in standard weather stations are pertinent to the microclimate experienced by trees or crops in a field.

An important feature of agroforestry systems is the interaction that occurs over time between the trees, the crops and the atmospheric and soil environment (Fig. 1). For this reason, most agroforestry models are 'dynamic' as they 'predict how a system unfolds with the passage of time' (Thornley and Johnson, 1990). Once the objective is clear, Connor (1983) writes that there are four steps in the development of a dynamic model.

1. There is a need to identify equations for the important flows of material and information.
2. There is a need to select values for all the parameters.

3. There is a need to set initial values for state variables.
4. The model is then run to solve the equations at appropriate time intervals.

In the example in Fig. 1, an important flow parameter may be the flow of water. The use of soil water by the tree and the crop can be expressed by equations with parameters. The initial state variables are likely to include the initial soil water content, and the change in soil water content over future time intervals is then calculated using a series of equations.

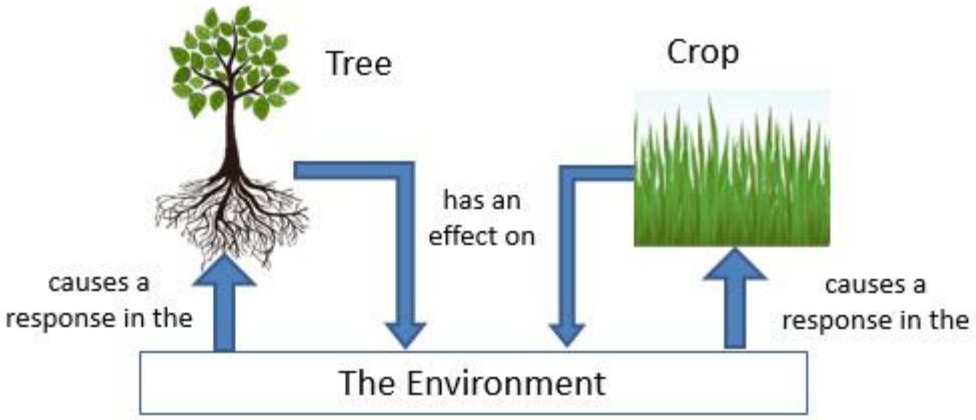

Figure 1 Schematic representation of the interaction between the trees, crops, atmosphere and soil environment that requires 'dynamic' models. Source: Adapted from Vandermeer (1989).

2.4.1 How complicated should a model be?

There are arguments in favour of both 'simple' and 'complicated' models (Boote et al., 1996). However to paraphrase Albert Einstein, a common approach is that 'things should be as simple as possible, but no simpler'. Box (1979) also argued positively for the use of parsimonious models and observed that 'all models are wrong, but some are useful'. Passioura (1973) also favoured simple crop simulation models with few parameters, as they were more 'testable'. By contrast, van Noordwijk and van de Geijn (1996) argue that the minimum number of parameters may increase over time as independent measures of those parameters become available and a model is used to address more specific questions.

Leinweber (1979) defined model complexity as a simple count of the number of arithmetic operations a model performs on input data, and he specified two sources of modelling error. One source relates to uncertainties in the input data. If the potential error of these is known, then the errors can combine in a way that can be predicted mathematically. Leinweber (1979) assumed that as the number of input parameters increased the margin for error also increased. In addition as the model becomes more complex, it can also become more difficult to describe the flows between spatial components, for example, how surplus of water in one part of the soil will be redistributed to other parts of the soil. The second form of error is a specification error where the model does not accurately describe what happens in practice. Leinweber argues that a model should only be made more complex if it is made more accurate. The assumption is that the specification error should decrease as the complexity increases. The net effect, as described by Palma et al. (2007b), is that there may be an optimum level of model complexity that minimises the total error due to simplistic assumptions and compound errors in the input data (Fig. 2).

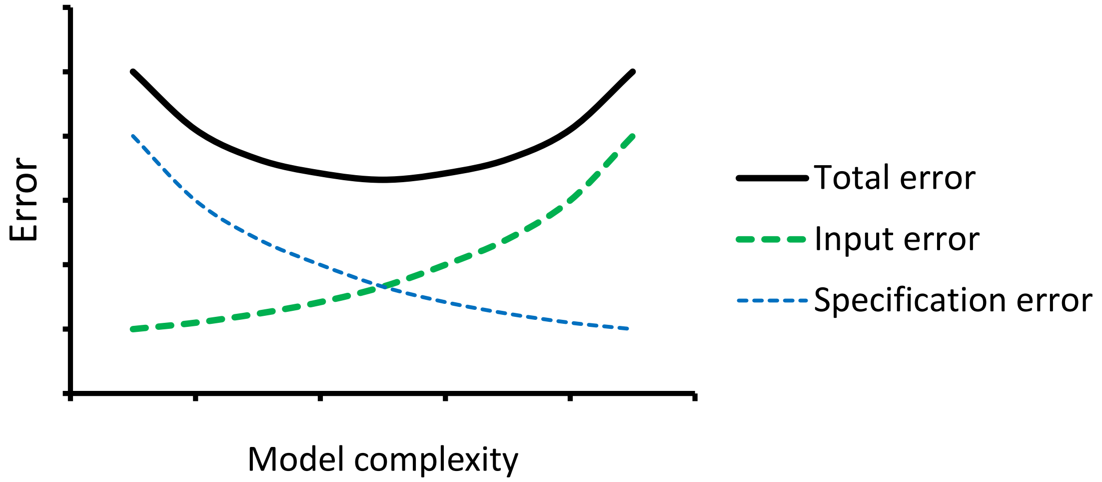

Figure 2 Relationship between model complexity and total error in the upscaling process. Source: Modified from Palma et al. (2007b) and Leinweber (1979).

Mechanistic models of tree and crop growth typically build on the physical and biological principles such as those described by de Wit in the Netherlands (de Wit, 1958; Bouman et al., 1996) and/or Monteith in the United Kingdom (Monteith, 1992). One of the first 'process-based' plant models called ELCROS was described by Brouwer and de Wit (1968). Jackson and Palmer (1972) described the results of a light interception model for different shapes of hedgerow orchards demonstrating the changes in diffuse and direct light interception with tree shape, alley width, season and latitude. Charles-Edwards and Thorpe (1976) also completed a similar analysis for a hedgerow apple orchard. Jackson and Palmer (1987) also described a diurnal light interception model to simulate light interception within an apple intercropping experiment.

2.4.2 Examples of a 'simple' agroforestry tree and crop growth model

One of the simplest mechanistic agroforestry models is Yield-SAFE which includes simple light capture algorithms and was originally designed to describe an alley cropping silvoarable system (van der Werf et al., 2007). As the time step for the model is a day, it is assumed that each part of the alley cropping field will receive some shade from the trees. The incoming daily solar radiation is assumed to be S (unit: MJ m^{-2} day^{-1}). The proportion of the radiation intercepted by trees (f_t) is then defined in terms of the leaf area index of the trees (LAI_t; unit: m^2 tree leaf area per m^2 plot) and a light extinction coefficient (k_t) (Eq. (1)) (van der Werf et al., 2007). Subsequent work showed that it was necessary to change the value of k_t as the trees grew (Keesman et al., 2011).

$$f_t = 1 - e^{-k_t \cdot LAI_t} \tag{1}$$

The potential radiation available below the trees (S_c) can then be defined using Eq. (2):

$$S_c = S\,(1 - f_t) \tag{2}$$

Within an alley cropping system it is assumed that silvoarable field is divided into a proportion that is cropped (A_c) and a proportion that is not cropped ($1-A_c$). The proportion of S_c that is intercepted by the understorey crop can therefore be derived from Eq. (3) where k_c is the radiation extinction coefficient of the crop and LAI_c is the leaf area index of the crop (m^2 crop leaf area per m^2 of cropped area).

$$f_c = A_c\left(1 - e^{-k_c\,.\,LAI_c}\right) \tag{3}$$

Whereas Yield-SAFE partitions the understorey into a crop and uncropped area, an alternative approach is to partition the agroforestry system in a tree-covered and non-tree-covered area. An example of this approach is described by Bergez et al. (1999) in the ALWAYS silvopastoral model which used photosynthetically active radiation (PAR). Building on the model of Jackson and Palmer (1979), the model partitioned the system into a proportion covered by a vertical projection of the tree canopy (A_t) and a proportion that was not ($1-A_t$). The mean daily PAR on the pasture (PAR_p) is then calculated as the sum of the sum of the diffuse radiation ($PAR_{diffuse}$) and the transmitted direct radiation ($PAR_{t,\ direct}$) within the tree canopy and the direct radiation (PAR_{direct}) for the remaining area (Eq. 4).

$$PAR_p = \left(PAR_{diffuse} + PAR_{t,direct}\right) A_t + PAR_{direct}(1 - A_t) \tag{4}$$

The value of $PAR_{t,direct}$ was derived from Eq. (5) where L_d is the leaf area density in the crown and s is the height of the crown.

$$PAR_{t,direct} = PAR_{direct}\, e^{\,(-0.5\,.\,L_d\,.\,s)} \tag{5}$$

The above five equations are examples of how simple agroforestry models can address the interception of solar radiation by a tree and a crop. Models such as Yield-SAFE and ALWAYS can also deal with water competition between the trees and understorey crops. Another example of a relatively simple agroforestry model is the coffee agroforestry model developed in MATLAB/Simulink (van Oijen et al., 2010) based on the BASic FORest simulator (BASFOR) tree model (van Oijen et al., 2005).

2.4.3 Complex agroforestry models

A limitation of the Yield-SAFE model is that it is only a one-dimensional model with some consideration of the horizontal extent of the arable crop (Fig. 3a). An example of a more complex two-dimensional model is the Water, Nutrient and Light Capture in Agroforestry Systems (WaNuLCAS) model as described by van Noordwijk and Lusiana (1999). The original version of the model included a four-layer soil profile (vertical), with four spatial zones (horizontal) (Fig. 3b), and calculation of the water and nitrogen balance and uptake by a crop and a tree. The model used a 'Stella Research' modelling shell with data inputs and outputs provided in Excel spreadsheets.

In an alley cropping context, whilst the two-dimensional WaNuLCAS model can be used to determine the effect of distance from a tree on crop yields, this particular version of the model assumes that light interception in a West-East direction will be the same as in a North-South alignment. Considerations of row alignment require a three-dimensional model. An early three-dimensional agroforestry model combined a detailed tree model called Hybrid (Friend et al., 1997) with a crop model called PARCH (Lawson et al., 1995). A more recently developed example of a three-dimensional agroforestry model is Hi-sAFe which combines a tree model with the suite of STICS crop models (Dupraz et al., 2005). The

Hi-sAFe model has a switchable toric symmetry module that replicates the simulated scene, allowing it to simulate isolated trees (toric symmetry fully off), tree hedges (toric symmetry off in one direction), alley cropping agroforestry (full toric symmetry) and forest edges (toric symmetry off in y and half-x axis), as well as crop and forest monocropping. In Hi-sAFe, root competition is addressed using a three-dimensional opportunistic tree root growth module based on a cellular automata algorithm. This allows the simulation of tree root systems that can adapt continuously to the soil environment as modified by the weather and the crop competition. Tree root pruning, tree branch pruning, tree stand thinning and a large panel of crop management schemes are also available. Another feature of Hi-sAFe is the possibility of considering the impact of a fluctuating seasonal water table on tree-crop competition (Lecomte et al., 2016).

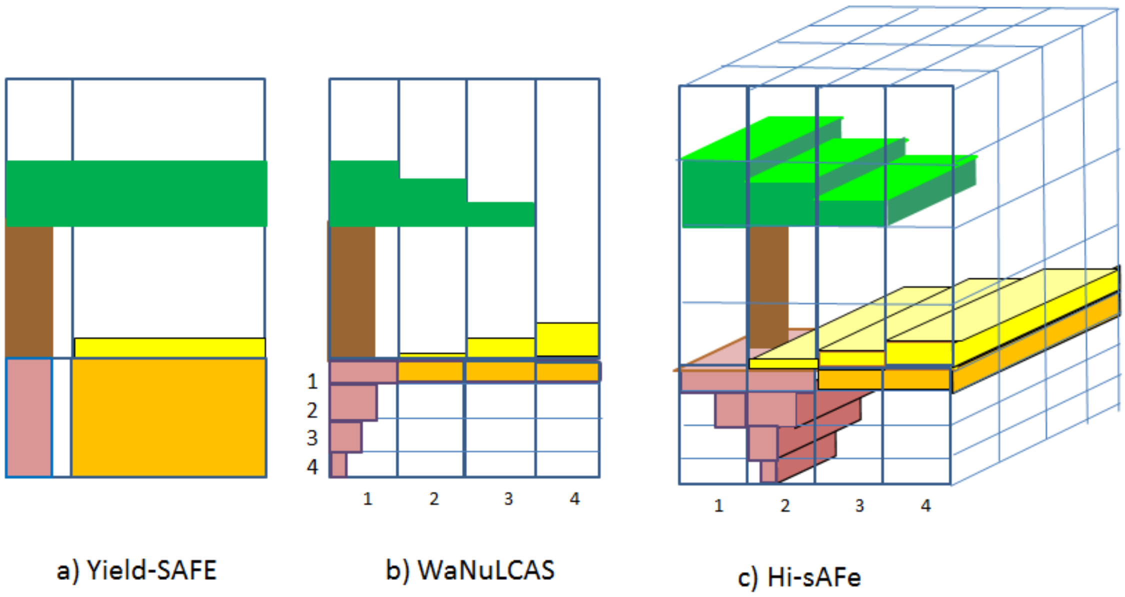

Figure 3 (a) The Yield-SAFE model comprises of two above-ground zones (crop and no crop) and one below-ground zone (soil depth). (b) The WaNuLCAS model described by van Noordwijk and Lusiana (1999) comprises four root zone depths and four distances from the tree. (c) Hi-sAFe is an example of a three-dimensional agroforestry model.

The initial use of the Hi-sAFe model included an examination of the clumpiness of leaves in trees (Talbot and Dupraz, 2012) and the simulation of walnut-wheat alley cropping for the duration of the tree life cycle (Dufour et al., 2013). More recently Dupraz et al. (2018) describe the use of the Hi-sAFe model to determine the best tree row orientations to maximise the systems outputs at various latitudes, from the tropics to boreal regions. This analysis showed that in terms of maximising understorey crop yields and uniformity, the best tree line orientation was East to West at low latitudes and North to South at high latitudes. Recent developments include the use of the model to assess the resilience of agroforestry systems to climate change, the nitrogen leaching control by the trees and the long-term C sequestration in the soils (Dupraz and Lecomte, 2017).

2.4.4 Flexibility of drawing on a wider user community

One potential advantage of the Hi-sAFe model is that the crop component is based on an established crop model called STICS, which is supported by a strong user community. Results reported by Artru et al. (2017) have demonstrated how different shading patterns affect the yields predicted using the STICS model. Luedeling et al. (2016) also describe some of the benefits in terms of flexibility in modelling agroforestry systems using the Agricultural Production Systems Simulator (APSIM) framework. The APSIM framework was initiated in 1994 and a 'next generation' of APSIM was released in October 2014 (Holzworth et al., 2018). Smethurst et al. (2016) describe the use of APSIM Next Generation framework to provide a two-dimensional (2D) representation of Gliricidia-maize intercropping, which is reported to describe accurately crop yield and water and soil carbon dynamics.

2.5 Architectural models of tree growth

Architectural models of tree growth are the fourth type of agroforestry model. De Reffye et al. (1995) describe the development of a canopy architecture model called AMAPmod by CIRAD in France, where tree architecture is described in terms of the form of 'growth units'. Models such as the 'FracRoot' model have also been used to describe below-ground root architecture (Ozier-Lafontaine et al., 1999). Lamanda et al. (2007) describe the use of three-dimensional architectural models to assess light availability and root bulkiness in coconut agroforestry systems in Vanuatu in the South Pacific.

2.6 Farm-scale management decision models

The fifth group of agroforestry models comprises models where the primary focus is to improve decision-making by farmers and others. Some comprise conceptual models, but many assume that profitability is an important determinant of whether a farmer will adopt a system.

2.6.1 Qualitative models of the system and farm decisions

Sinclair and Walker (1998a,b) describe a method to model indigenous ecological knowledge on agroforestry. They demonstrate that formal representation of such models can increase the coherence, consistency and completeness of our understanding of agroforestry systems. Meylan et al. (2013) also describe the development of a conceptual model to identify the constraints and trade-offs associated with four types of farmers practising agroforestry with coffee production. The model includes environmental factors (e.g. climate), management factors, agronomic and hydrological processes, and outputs such as yield, gross margin and soil erosion losses. The process results in a series of system-flow diagrams showing the relationships between the various factors, processes and outputs. They argue that this can serve as a preliminary stage before attempting to identify the key points of potential interventions in the system. In a similar way, flow diagrams were developed by Acuña et al. (1997) in their development of a knowledge-based system model to create decision trees related to agroforestry grants in Spain. Moral et al. (2014) in Spain also examine the rationale for on-farm decisions drawing on a survey of dehesa management based on a Strength, Weaknesses, Opportunities and Threats (SWOT) model. The survey identified 68 potential threats to the system, and a Rasch ranking methodology was used to develop a model that describes the most important threats.

2.6.2 Financial models

It is possible to undertake a financial cost-benefit analysis of agroforestry systems without a detailed biophysical model of tree and crop yields. For example Dube et al. (2002) describe the financial benefits and costs of a eucalyptus agroforestry system in Brazil. However in their review of financial models of silvoarable systems, Graves et al. (2005) found five models that could incorporate yield and financial data. The models included WaNuLCAS with a financial component (van Noordwijk and Lusiana, 1999), POPMOD (Thomas, 1991), ARBUSTRA (Liagre, 1997), the Agroforestry Estate Model (Knowles and Middlemiss, 1999) and the Agroforestry Calculator (Agriculture Western Australia and Campbell White and Associates Pty Ltd, 2000). Graves et al. (2005) found that whilst ARBUSTRA and the Agroforestry Calculator relied on direct inputs of yield data, WaNuLCAS, POPMOD and the Agroforestry Estate Model contained biophysical models of differing complexities that were used to generate the yield data for the financial analyses. For WaNuLCAS and Agroforestry Estate Model, this information flowed in one direction from the biophysical component of the model to the financial component of the model. In the POPMOD model, it was possible for management feedback from the financial component of the model, to link back to the biophysical component and modify the yields obtained.

The Farm-SAFE model (Graves et al., 2011) developed during the SAFE project is an example of a financial model, developed to evaluate the profitability, practicality and feasibility of silvoarable systems from a farmer perspective. It used annual tree and crop yield data on arable, forestry and agroforestry systems, derived from the Yield-SAFE model, which was then used to compare the financial benefits and costs. As it is a farm-scale model, it can be used to model different arable, forestry and agroforestry systems across a farm reflecting, for example, contrasting levels of soil fertility. Another example of a recent model combining financial and yield data for grass-oak tree systems in Spain and Portugal is Forage-SAFE (García de Jalón et al., 2018a). This uses a relationship for grass growth at varying distances from an oak tree to calculate what the optimal stocking rate should be for livestock at different tree densities and grass productivity levels.

One of the important points in completing a useful financial analysis of an agroforestry system is the ability to complete analogous analyses of ‘counterfactual’ forestry and/or agricultural systems. Thus, for example, Farm-SAFE, ARBUSTRA and POPMOD provide a financial assessment of arable and forestry systems against which the financial performance of agroforestry can be compared. One effect of this is that most agroforestry financial models are effectively combined agricultural, agroforestry and forestry models, for example, they can compare a wide range of land uses. In order to account for the impact of the different systems on labour and machinery costs, it is generally accepted that the comparison should be based on net margins, rather than gross margins. Freya et al. (2013) also describes how the impact of changes in price, after the establishment of an agroforestry or forestry system, can affect management choice using a stochastic and ‘real options’ model. Farm-SAFE, for example, contains the option of changing future grants, prices and costs either in a continuous phased or discontinuous one-off pattern from a specified year in the future.

2.6.3 Economic and social welfare models

Whilst financial models can be used to compare the attractiveness of an agroforestry system with arable or forestry systems for a farmer, the attractiveness of agroforestry from a societal perspective requires consideration of wider societal costs and benefits. Possible benefits may be increased carbon sequestration or reduced nitrate leaching which does not have a readily available market value. Through the use of cost-benefit analysis and environmental valuation data, it is possible to impute values for many of the outputs that do not have immediate market value. Since 2014, Farm-SAFE has been developed to incorporate non-market societal costs and benefits of arable, forestry and agroforestry systems by incorporating life cycle assessment and valuation data. Life cycle assessment data can be linked with management decisions to quantify the environmental burdens associated with tree and crop production in the modelled arable, forestry and agroforestry systems. This is then linked with valuation data derived using a benefits-transfer approach in order to quantify the non-monetary value of changes in carbon sequestration, and erosion, nitrate and phosphorus emissions to water (García de Jalón et al., 2018b). Dhakal et al. (2007) also describe the use of a constrained welfare maximisation model to identify the opportunity of farmers implementing agroforestry in Nepal. The analysis was based on a household income model, a household production model and a community welfare model.

2.6.4 Adoption models

The adoption of agroforestry is not solely determined by a financial and economic analysis. Lovrić et al. (2018) describe the use of an analytic network process to quantify the driving forces between agroforestry uptake in Mediterranean Europe in environmental, economic and social areas.

2.7 Landscape models

A common question in government-sponsored research is to determine the effect of the widespread uptake of agroforestry. This can take place at a landscape, regional or national scale. Models such as ARBUSTRA and Farm-SAFE can be used as landscape models since they are able to model a range of different arable, forestry and agroforestry systems under different environmental and management conditions. The results can then be aggregated to the landscape scale by summing the outputs of the different systems. The biophysical assessments are typically based by running versions of the biophysical, financial and economic models described above within a geographical information system (GIS) framework. Such an approach was used in the SAFE project (Dupraz et al., 2005) by Palma et al. (2007a). In the AGFORWARD project (Burgess and Rosati, 2018), a similar approach was used by Kay et al. (2018). Another example of a landscape model linking GIS with other models is Polyscape (Jackson et al., 2013). The Polyscape model uses algorithms to determine the effect of land cover changes, such as agroforestry, on flooding, soil erosion, carbon storage and agricultural production. In China, Zeng et al. (2018) describe the use of GIS with a land-water-environment model to determine the effect of afforestation or increased agricultural production. It is interesting that they refer to their model as an agroforestry ecosystem model – whereas in reality it is a model that can address forestry, agroforestry and agriculture.

3 Example of how agroforestry modelling can enhance sustainability

In Europe during the past two decades, there have been two large agroforestry projects that involved modelling. The Silvoarable Agroforestry For Europe (SAFE) project ran from 2001 to 2005 (Dupraz et al., 2005). The AGroFORestry that Will Advance Rural Development (AGFORWARD) project ran from 2014 to 2017 (Burgess and Rosati, 2018). Within the SAFE and AGFORWARD projects, the project aim was to determine the effect of different agroforestry systems at farm and landscape scales. The intention was to look at both food and fibre production and some of the most important regulating services. The stages of identifying and using an agroforestry model, in the case of the SAFE project, was described by Graves et al. (2011) and is illustrated in Fig. 4. The stages involve (1) establishing criteria for model, (2) reviewing existing models, (3) developing a new model (if required) and (4) using the model. This process is then discussed using the modelling activity described by García de Jalón et al. (2018b).

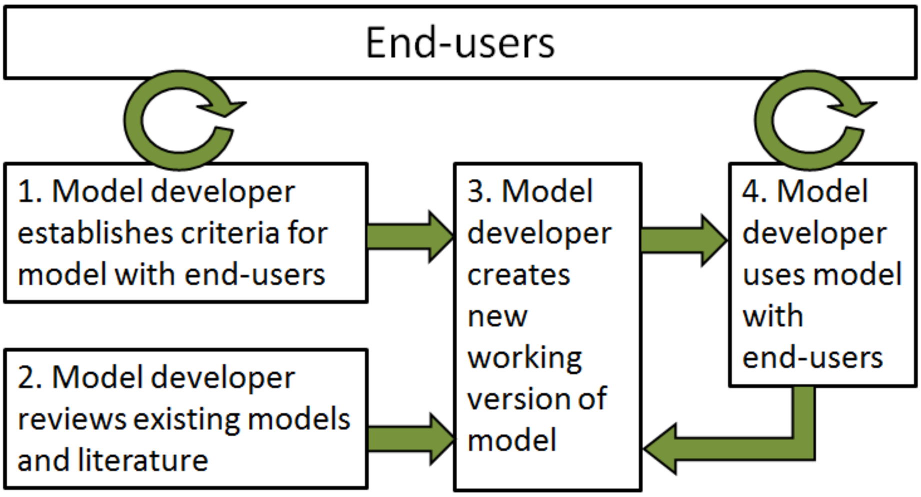

Figure 4 Schematic showing how the development and use of an agroforestry model can be based on feedback from end users. Source: Adapted from Graves et al. (2010).

3.1 Establish criteria

Within the AGFORWARD project one of the objectives was to compare the financial attractiveness of arable, forestry and a silvoarable poplar system in the United Kingdom, and to determine the social impact of environmental externalities (Table 3). Using a framework described by Graves et al. (2005), the criteria for the model included requirements related to (1) the model background, (2) the systems to be modelled, (3) the objective of the economic analysis, (4) viewpoint of the analysis, (5) spatial scale, (6) temporal scale, (7) the generation and use of biophysical data, (8) the model platform and interface and (9) the input requirements and outputs generated.

Table 3 Example criteria for a societal comparison of agroforestry with forest and agricultural systems (based on model characteristics described by Graves et al., 2005)

Model characteristic	Example option
Background	
Language	English
Initial primary use	Research
Systems modelled	
Components of system	Agriculture, forestry, and silvoarable
Number of systems	One agriculture, one forestry, and one silvoarable system
Objectives of analysis	Comparison of different systems
Viewpoint of analysis	Micro-economic (i.e. perspective of land manager) and macro-economic (i.e. perspective of society)
Spatial scale	Comparison of one-hectare plots
Temporal scale	
Time-step	Daily
Time period considered	A tree rotation of 30 years
Generation and use of biophysical data	
Biophysical-economic links	Bio-economic model with two-way information flow
Nature of biophysical model	A mechanistic model which includes growth processes
Platform and interface	
Model platform	Spreadsheet
Model interface	Spreadsheet
Inputs and outputs	
Inputs requirements	Relatively low data requirements
Outputs	Biophysical and economic

3.2 Review existing models

As described in Section 2.6.2, Graves et al. (2005) reviewed five models of silvoarable economics at the beginning of the SAFE project. As a result of that analysis it was decided to develop a spreadsheet-based model building on the key capabilities of the POPMOD and the ARBUSTRA models, which was subsequently called the Farm-SAFE model (Graves et al., 2011). However, as Farm-SAFE was developed purely as a financial model, it had no means of generating yield data. Hence the biophysical Yield-SAFE model was also developed to provide annual tree and crop yield data. Based on this review, the Yield-SAFE and Farm-SAFE models were also selected for use in the AGFORWARD project. However, whereas the SAFE project focussed on the financial performance of silvoarable systems, the aim of the AGFORWARD project was to complete financial and economic analyses of a wider range of agroforestry systems.

3.3 Create new working version of the models

Hence since 2014 in the AGFORWARD project, researchers worked on the Yield-SAFE and Farm-SAFE models to develop new algorithms to describe important environmental externalities such as greenhouse gas emissions, carbon sequestration, soil erosion, and nitrogen and phosphorus losses (García de Jalón et al., 2018b). The method for comparing the societal effect of a silvoarable agroforestry system with forestry and arable systems comprised five stages: (1) simulation of the biophysical growth of trees and crops for an experimental plot case study using Yield-SAFE, (2) quantification of the environmental externalities (Yield-SAFE and Farm-SAFE), (3) assessment of financial performance (Farm-SAFE), (4) conversion of the environmental externalities into monetary terms (valuation data) and (5) assessment of the societal performance of the different land use systems through an aggregate financial and economic analysis (Farm-SAFE). Each stage was addressed by different models or approaches (Table 4).

Table 4 Summary of the key modelling activities to compare the societal effect of a silvoarable agroforestry system with forestry and arable systems (based on García de Jalón et al., 2018b)

Modelling activity		Model or approach	Units	Reference
Crop and tree yields	Crop and timber yield	Yield-SAFE model	t dry matter ha^{-1} y^{-1}	Van der Werf et al. (2007)
Financial performance	Financial performance	Farm-SAFE model	€ ha^{-1} y^{-1}	Graves et al. (2011)
Quantifying environmental externalities	Greenhouse gas emissions	Life cycle assessment of greenhouse gas emissions	t CO_2e ha^{-1} y^{-1}	Williams et al. (2010)
	Carbon sequestration	Approach based on the simulated biomass growth	t CO_2e ha^{-1} y^{-1}	Nair (2011)
	Soil loss due to erosion	Revised Universal Soil Loss Equation (RUSLE)	t soil ha^{-1} y^{-1}	Palma et al. (2007b)
	Nitrogen surplus	Nitrogen balance model	kg N ha^{-1} y^{-1}	Palma et al. (2007b) and Feldwisch et al. (1998)
	Phosphorus surplus	Phosphorus balance model	kg P_2O_5 ha^{-1} y^{-1}	Garcia Jalon et al. (2018b)
Conversion of environmental externalities to monetary terms	Societal economic benefits and costs	Benefit transfer method	€ (t CO_2e)$^{-1}$ € (t soil)$^{-1}$ € (kg N)$^{-1}$ € (kg P_2O_5)$^{-1}$	
Economic performance		Farm-SAFE model	€ ha^{-1} y^{-1}	Garcia Jalon et al. (2018b)

3.4 Use of the model

This section provides an example of the use of an agroforestry model to compare the full societal value of the agroforestry, arable and forestry systems based on an experimental case study site at Silsoe in Bedfordshire in the United Kingdom as described by Burgess et al. (2005) and García de Jalón et al. (2018b). The daily time step Yield-SAFE model was used with local weather data derived from the CliPick tool (Palma, 2017). The model was then calibrated to local conditions by adjusting the light extinction coefficient, harvest index and water use efficiency to match model predictions to observed yield and growth data obtained in local tree-only and crop-only systems (see Graves et al., 2007 for more detail). For the tree-only system, the observed data for model calibration were poplar tree heights and diameters obtained for a forest treatment at the Silsoe experimental site (see 'Observed forestry data', Fig. 5). For the crop-only system the observed data were taken from statistics on local agriculture, for example, Agro Business Consultants (2015). The model of tree height and diameter with and without intercropping is shown in Fig. 5. From this calibration to local conditions, Yield-SAFE was then used to predict the tree and crop yields for arable, forestry and silvoarable systems over a 30-year time horizon. These data were then used as inputs into the Farm-SAFE model, which was used to calculate the financial and economic outputs of the arable, silvoarable and forestry systems.

The important financial outputs of the modelling exercise are described in Table 5. The results show that, in the absence of grants, the financial profitability of the arable system expressed as an equivalent annual value (€315 ha^{-1}) was substantially higher than for the silvoarable (€120 ha^{-1}) and forestry (€62 ha^{-1}) systems (Table 5). However, after the quantification and assignment of monetary values to the non-market costs and benefits associated with the arable, forestry and agroforestry systems, it became evident that the arable system was also associated with high environmental costs, particularly in terms of the nitrogen surplus (−€186 ha^{-1}). The agroforestry and forestry systems on the other hand were associated with environmental benefits in the form of carbon sequestration (€30 ha^{-1} and €35 ha^{-1} respectively), whilst also having low costs associated with the nitrogen surpluses (−€28 ha^{-1} and €0 ha^{-1} respectively). On this basis, the net annual societal benefit of the silvoarable system (€108 ha−1) was found to be slightly higher than that for the arable (€98 ha^{-1}) and the forestry systems (€95 ha^{-1}). Hence this analysis highlights that there is a rationale for providing public support for agroforestry in terms of the environmental benefits.

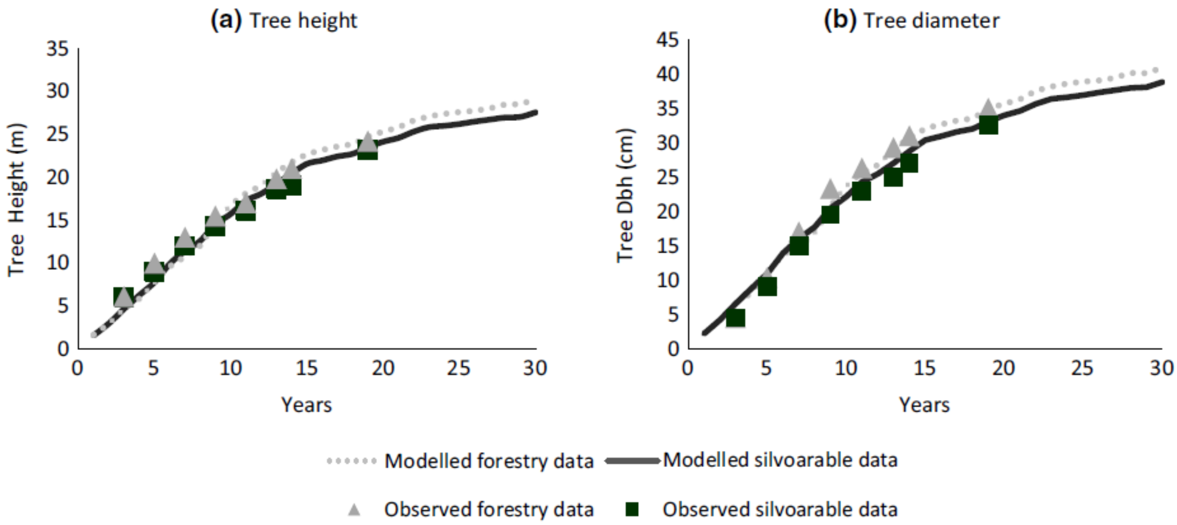

Figure 5 Observed and modelled height (a) and diameter at breast height (Dbh) (b) of the poplar trees in the forestry and silvoarable system in Bedfordshire in the United Kingdom. Source: Adapted from Garcia de Jalon et al. (2018b).

Table 5 Financial and economic equivalent annual value (EAV) of an arable, forestry and silvoarable system in Bedfordshire in the United Kingdom

	Arable[a]	Silvoarable[b]			Forestry[c]
		Crop component	Tree component	Combined	
Financial analysis					
EAV_F (€ ha^{-1} yr^{-1})	315	91	29	120	62
Environmental externalities					
CO_2eq emissions (t CO_2eq ha^{-1} yr^{-1})	2.4	1.1	0.0	1.1	0.0
CO_2eq sequestration (t CO_2eq ha^{-1} yr^{-1})	0.0	0.0	4.0	4.0	4.7
Soil erosion losses by water (t soil ha^{-1} yr^{-1})	0.4	-	-	0.2	0.2
Nitrogen surplus (kg N ha^{-1} yr^{-1})	24.6	-	-	2.2[d]	0.0
Phosphorus surplus (kg P_2O_5 ha^{-1} yr^{-1})	8.0	-	-	0.4	0.0
Economic analysis					
EAV CO_2eq emissions (€ ha^{-1} yr^{-1})	-20	-11	0	-11	0
EAV CO_2eq sequestration (€ ha^{-1} yr^{-1})	0	0	30	30	35
EAV Soil erosion losses (€ ha^{-1} yr^{-1})	-3	-	-	-2	-2
EAV Nitrogen surplus (€ ha^{-1} yr^{-1})	-186	-	-	-28	0
EAV Phosphorus surplus (€ ha^{-1} yr^{-1})	-8	-	-	-1	0
EAV_E with externalities (€ ha^{-1} yr^{-1})	98	-	-	108	95

[a] Arable system was a rotation of winter wheat, winter wheat, spring barley and oilseed rape
[b] Silvoarable system had the same rotation as the arable system with poplars planted at 156 trees per hectare.
[c] Forestry system had poplars planted at a density of 156 trees per hectare but no arable understorey
[d] This is the balance of surplus from the crop minus the uptake of the tree

4 Current agroforestry modelling needs and potential trends

The above sections have examined the current state of agroforestry modelling and provided an example of the use of agroforestry models to compare the market and non-market benefits of agroforestry relative to arable and forestry systems. Looking to the future, this final section considers current agroforestry modelling needs and potential trends. A first point to make is that agroforestry models have a role beyond just agroforestry. The other points considered include the accessibility of agroforestry models, the benefits of long-term support, the need to know when to stop model development, the availability of data and the societal assessments.

4.1 Agroforestry models are particularly useful as they are forest to agriculture continuum models

A particular strength of agroforestry models is that they can model the whole continuum from pure forestry via a range of agroforestry systems to rotational and monoculture agriculture. They have a use beyond just agroforestry. In fact agroforestry models can be used to compare land use decisions across a range of land uses that include both agriculture and forestry such as described by Burgess et al. (2012) for a case study area in the United Kingdom.

4.2 Publicising and making models available

Matthews et al. (2002) argue that crop models can be considered to pass through infancy, juvenile, adolescence and maturity stages. Hence they question at what stage is a model ready to find gainful employment beyond the environment where it was initially raised? As described earlier, able agroforestry modellers should be open to use models that they have not developed. When someone needs to extract a screw, and they only have a hammer in their toolbox, this does not mean that the hammer is the best and only way for extracting the screw. Instead, the individual would be well advised to obtain a screwdriver to make the job successful. It is therefore important, as argued by Boote et al. (2006), that agroforestry modellers should be clear about the capabilities and limitations of both their own models and other alternative models on the market. It also means that models should be publicised and be made as widely available as possible. Details on how to access some of the models described in this chapter are provided in the final section.

4.3 The use of models depends on the research communities

The development, use and longevity of agroforestry models as a research tool seem to be dependent on long-term research projects and/or funding. For example, the development and use of the Hi-sAFe, Yield-SAFE and Farm-SAFE models in Europe has been dependent on the SAFE (2001–05) and the AGFORWARD (2014–17) projects. Another example is the AgMIP models developed from the International Consortium for Agricultural Systems Applications (ICASA) project between 1993 and 2011 (Jones et al., 2017).

4.4 The need to know when to stop developing a model

The second Utz law of computer programming states that ‘if a programme is useful it will have to be changed’ (The Economist, 1986). It can be difficult to know when it is time to stop developing and calibrating a computer model and when to validate and use it (Boote et al., 1996). Calibration refers to the fine-tuning of model parameters to make it appropriate for a particular location or design. Validation refers to the testing of the model outputs, after calibration, using independent datasets. Passioura (1973) has argued that comprehensive crop models are works of art, quoting a conference comment by de Wit that developing crop models are ‘the most cumbersome and subjective technique of curve fitting . . . that can be imagined’. Passioura also argues that it can be easy in model development to generate new parameters rather than new hypotheses. This chapter has highlighted those agroforestry models that have been developed, used and written-up in the form of a scientific report or paper. There are probably agroforestry models that have been developed but have not been reported.

4.5 Agroforestry models and data

The use of agroforestry models is nearly always constrained by a lack of accurate data either in the forms of inputs, for parameters or for calibration and validation of the model. One potential development which may help address this is the increasing availability of detailed remote sensing data. Time series of such data may be useful to help calibrate agroforestry models. In addition to a lack of biophysical data, the wide range of agroforestry systems mean that it can also be difficult to find financial data related to tree management. A difficulty in finding financial information of the timber value of trees is a particular problem (Burgess et al., 2017). Hence, one benefit of agroforestry modelling is that it provides a means by which biophysical and economic knowledge on agroforestry systems can be generated and shared. A major achievement would be to collect such data in a format that is transparent and easily used by farmers.

4.6 Societal assessments

An increasing need is to broaden the scope of agroforestry model assessments so that the full costs and benefits of land use decisions can be identified. Such modelling is challenging because of its breadth and it is still in its early stages, for example, García de Jalón et al. (2018b). Such evaluations are likely to be of increasing relevance to society given current and future societal pressures on the environment.

5 Acknowledgements

6 Where to look for further information

The four main agroforestry models described in this chapter are the Yield-SAFE suite of models, Hi-sAFe, WaNuLCAS and APSIM. Details on the source of these models are outlined below.

The Yield-SAFE and Farm-SAFE models used in the SAFE and AGFORWARD project is available from staff at Cranfield University (P.Burgess@cranfield.ac.uk) and from the AGFORWARD plot-scale modelling web page: http://www.agforward.eu/index.php/en/wp6.html.

The three-dimensional Hi-sAFe model is developed by INRA France and is freely available from: https://www1.montpellier.inra.fr/wp-inra/hi-safe/en/. Registration is required to download the model. A new version including the APEX crop models is currently prepared. The Hi-sAFer toolbox is available to process easily the model outputs (Wolz, 2018).

WaNuLCAS (https://www.worldagroforestry.org/output/wanulcas-model-water-nutrient-and-light-capture-agroforestry-systems) is an open source, free access model that combines a spreadsheet data pre-processing part with a STELLA-based dynamic model.

The APSIM (https://www.apsim.info/AboutUs.aspx) and DSSAT Cropping System Model http://dssat.net/downloads/dssatv46) are both open source and allow free access to model source code to enable community-based development. The framework is freely available for non-commercial use and it can be operated using Microsoft Visual C++.

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