Coffee agroforestry systems in Central America: II. Development of a simple process-based model and preliminary results

Marcel van Oijen · Jean Dauzat · Jean-Michel Harmand · Gerry Lawson · Philippe Vaast

Abstract Research on coffee agroforestry systems in Central America has identified various environmental factors, management strategies and plant characteristics that affect growth, yield and the impact of the systems on the environment. Much of this literature is not quantitative, and it remains difficult to optimise growing area selection, shade tree use and management. To assist in this optimisation we developed a simple dynamic model of coffee agroforestry systems. The model includes the physiology of vegetative and reproductive growth of coffee plants, and its response to different growing conditions. This is integrated into a plot-scale model of coffee and shade tree growth which includes competition for light, water and nutrients and allows for management treatments such as spacing, thinning, pruning and fertilising. Because of the limited availability of quantitative information, model parameterisation remains fraught with uncertainty, but model behaviour seems consistent with observations. We show examples of how the model can be used to examine trade-offs between increasing coffee and tree productivity, and between maximising productivity and limiting the impact of the system on the environment.

Keywords Yield · Environmental impact · Climate · Soil · Management · Sensitivity analysis

M. van Oijen (✉)
Centre for Ecology and Hydrology (CEH-Edinburgh),
Bush Estate, Penicuik EH26 0QB, UK
e-mail: mvano@ceh.ac.uk

J. Dauzat · J.-M. Harmand
CIRAD, Montpellier, France

G. Lawson
NERC, Swindon, UK

P. Vaast
CATIE, Turrialba, Costa Rica

Introduction

Coffee (*Coffea arabica*, L.) is grown in monoculture and as part of agroforestry systems. In Central America, in recent decades, there had been a trend towards growing coffee in high-input monocultures, but agroforestry systems are again becoming more common (Muschler and Bonnemann 1997). A main reason for the trend reversal is that farmers now focus less exclusively on coffee yield, and aim for a wider spectrum of ecosystem services, which can be supported by including shade trees. However, it is difficult to optimise the selection of shade tree species and the management of the agroforestry system.

Process-based modelling might benefit the development of coffee agroforestry systems. The purpose of modelling managed ecosystems is typically twofold. First, the process of model building and parameterisation highlights gaps in our knowledge, which may help in setting the research agenda. Secondly, the completed model may be used to explore how different factors,

under human control or not, affect the productivity and environmental impact of the system. Here, we describe the development of a model for coffee agroforestry systems aimed at exploring the systems' response to strategic management decisions (fertilisation level, shade-tree species and density, pruning and thinning regimes), regional differences in growing conditions (weather and soil) and environmental change (climate and atmospheric composition). To meet these goals, the model needs to be able to simulate a full rotation of coffee growth, which takes typically 10–25 years in our area of interest, Central America.

Process-based modelling of crop growth started in the 1960s, followed by the first forest models in the early 1970s and agroforestry models another decade later (Bouman et al. 1996; Muetzelfeldt and Sinclair 1993). Many early crop models were highly complex and parameter-rich, but more recently the focus has shifted towards simpler process-based models which proved easier to parameterise and provided more robust predictions (Bouman et al. 1996). Recent reviews of agroforestry models do not reveal a similar trend to greater model simplicity (Matthews et al. 2004; Muetzelfeldt and Sinclair 1993; Young 1997). In fact, the reviewers suggest that even the most complex generic agroforestry models like WaNulCas (Van Noordwijk et al. 2004) and HyPar (Mobbs et al. 1998) should be further refined, although they admit that model users tend to find it hard to parameterise current model versions for their own systems (Matthews et al. 2004). Here, we take the view that model complexity should be commensurate with data availability. In a companion paper (Van Oijen et al. 2010), we reviewed the availability of quantitative information on coffee agroforestry systems, and concluded that parameters for many physiological and ecological processes are not well known. We therefore aim for a simple model, realising that ongoing research may justify adding complexity at a later stage.

Thus far, no models have been developed specifically for the coffee agroforestry system. For unshaded coffee plants, 3D-architectural models have been developed (Dauzat et al. 2001; Dereffye 1983) which focus on within-season dynamics of light and water use by the plants. These models are useful tools for analysing the aboveground morphological aspects of coffee growth and resource acquisition, but they are too complex to serve as components in a simple full-rotation agroforestry model. Likewise, a model for

Erythrina poeppigiana, a common shade-tree species for coffee, exists, but again with a focus on short-term radiation distribution (Nygren 1993). Notwithstanding the absence of ready-made coffee and shade-tree models, many algorithms developed for simple crop and forest models (for example, Van Oijen et al. 2004, 2005) have general validity and may be used as elements in a coffee agroforestry model.

When deciding on the structure of a model, we need to specify which factors are considered and which are excluded. Our aim is to develop a process-based model that incorporates only the major characteristics of both coffee and shade trees that affect their productivity and the impact the system has on the environment. We therefore did not aim to include pests, weeds and diseases in the model, nor the effects of soil toxicity and air pollution. Instead, we focus on potential productivity, defined as growth unlimited by factors other than light, water, N and only constrained by local soil and weather conditions and by site management. We concentrate on coffee and tree genotypes used in Central American coffee growing regions of various altitudes (which differ climatically mainly in temperature), with different levels of availability of water and nitrogen, and different management regimes. Specifically, the following growing conditions are to be addressed as inputs by the model:

- Weather conditions: temperature, rain, light, humidity, wind
- Soil conditions: initial organic matter and nitrogen content, water retention characteristics, slope
- Tree management: choice of species, density, thinning regime, pruning regime
- Coffee management: rotation length, N-fertilisation, pruning regime

The domain of applicability of the model is all coffee agroforestry systems where plant growth and soil dynamics are mainly determined by the above input factors. The following characteristics of the agroforestry system are to be quantified as model outputs:

- Productivity: coffee bean yield (dry matter), tree stem volume
- Environmental impact: rate of N-leaching to groundwater and of N-emission to the atmosphere, rate of loss of organic carbon and nitrogen in surface runoff
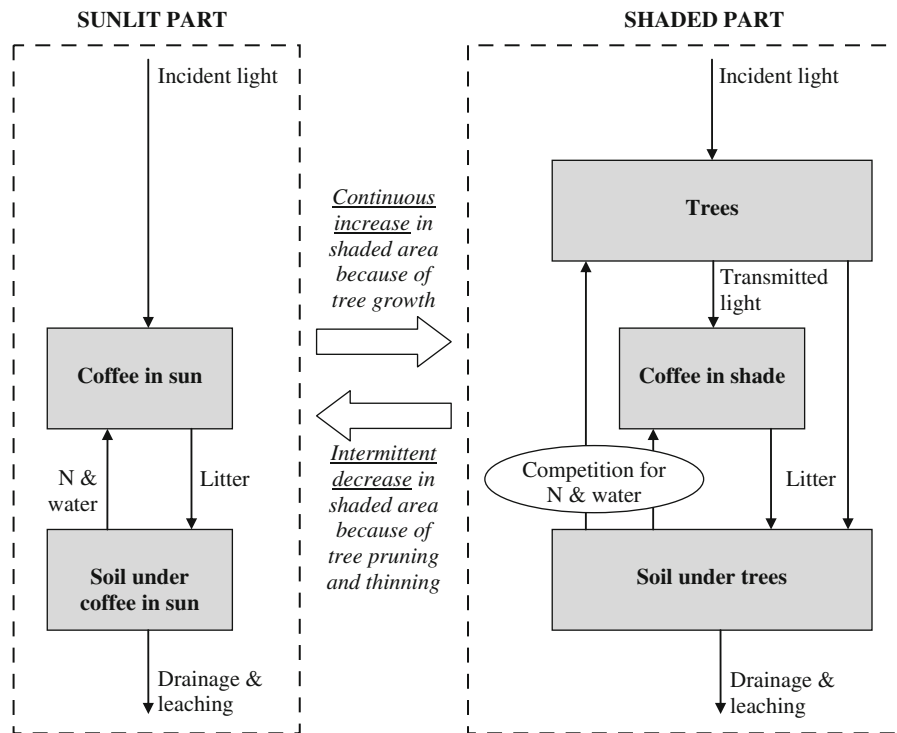
Fig. 1 Resource fluxes in coffee agroforestry systems. When tree cover is less than 100%, part of the field is *not shaded* (*left*) and competition for resources only takes place in the *shaded* part (*right*). The *shaded part* expands because of tree growth and contracts because of tree management

Coffee agroforestry systems typically have low bean yield in the 1st years and in the years following coffee pruning. Wood production is also not constant with tree cover initially increasing but repeatedly being reduced by pruning and thinning. The system thus is highly dynamic, and we try to account for this by modelling time courses of coffee and tree growth from planting to the end of the rotation period.

In this paper we shall present such a model and evaluate whether the model can account for commonly observed behaviour of coffee agroforestry systems in Central America.

A dynamic model for coffee agroforestry systems

The system

A schematic view of the main components and interactions in coffee agroforestry systems is depicted in Fig. 1. The scheme emphasises that coffee agroforestry fields are not homogeneous: a fraction of the

coffee plants will not be shaded when the trees are still young or after the trees have been pruned or thinned back. In the tree-covered part of the field there will be competition for resources between trees and coffee. The major resources required by both plant types are CO_2, light, water and nutrients. Because of adequate atmospheric mixing, competition for CO_2 is negligible, whereas the competition for light is generally asymmetric with tree canopies having first access to incident radiation and shade-coffee only intercepting light transmitted by the trees. On the other hand, there is full competition for soil resources because the root systems of the two plant types at least partly occupy the same soil volume. Lack of homogeneity in coffee growth because of incomplete tree cover translates into corresponding differences in soil characteristics, with only the tree-covered part of the field receiving tree litter, and receiving coffee litter at a different rate and quality compared to the unshaded part. A simple dynamic model for coffee agroforestry systems aimed at evaluating the system's response to changes in environmental conditions or management regimes

needs to represent the key competition processes and spatial heterogeneity, and we suggest it be at least at the level of complexity shown in Fig. 1.

Overall model structure and implementation

The long period of growth to be simulated, 10–25 years, calls for a model that ignores diurnal time courses and details in the dynamics of coffee and tree architecture. We therefore did not follow the examples of the only dynamic models produced for coffee thus far, i.e. the 3-dimensional functional-architectural models of Dereffye (1981, 1983) and Dauzat et al. (2001), which were developed to simulate coffee growth over short time periods. On the other hand, given the requirements concerning model input (weather, management) and output (productivity and various fluxes of C, N and water) the model could not be made overly simple. We thus chose to construct a daily time step model, using where possible pre-existing submodels for the different components in the system. The scheme in Fig. 1 shows the basic structure of the model. The scheme is incomplete as many fluxes of water and N are not shown, nor are any of the physiological and physical processes within plant or soil components represented, but these details will be supplied in the present section.

We implemented the model in MATLAB/Simulink, which is software designed for numerical modelling and analysis of dynamic systems.

Model structure is supposed to be generic to AFS in CA with the possibility to express differences between shade tree species through different parameter values. The model thus allows simulation of tree species grown purely for shade as well as those that fix nitrogen or provide timber. However, in this paper we shall only give examples of simulations for six shade-tree species: *Cordia alliodora*, *Erythrina poeppigiana*, *Eucalyptus deglupta*, *Gliricidia sepium*, *Inga densiflora*, *Terminalia ivorensis*. *E. poeppigiana*, *G. sepium* and *I. densiflora* fix nitrogen, while *C. alliodora*, *E. deglupta* and *T. ivorensis* provide timber. All six tree species are common in Central American agroforestry systems.

In the following, we shall discuss the various components of the model, focusing in particular on parts of the model where novel approaches were used.

Weather data

The model operates on a daily time step and takes as input daily values of weather conditions: radiation, temperature, precipitation, humidity and wind speed. The longest continuous time series available to us, with daily data for all five weather variables, was from the CATIE research station at Turrialba, Costa Rica (9.53°N, 8.38°W, alt. 602 m). The data cover the years 1998–2004, with mean temperature 23.4°C, rain 8.6 mm d^{-1}, vapour pressure 2.36 kPa, global radiation 15 MJ m^{-2} d^{-1} and wind speed 0.75 m s^{-1}. This dataset was used for most of the simulations in this paper except for simulations aimed at quantifying the impact of regional weather differences in Central America. For these simulations, we used the long-term mean monthly average weather data assembled in the FAOCLIM database (FAO 1995). For regions above 600 m altitude, where coffee is typically grown, the FAOCLIM database includes 8 stations in Costa Rica, none in Nicaragua and 16 in Guatemala. For all variables except rainfall we used linear interpolation between the monthly means to derive time series of daily weather. For rainfall this procedure is an oversimplification because of the sensitivity of coffee flowering to the sudden onset of rains after the dry period. Using data on daily rainfall from two experimental trial sites in Costa Rica, we therefore derived a simple stochastic algorithm for generating time series of daily rainfall from monthly means (Appendix 1), which can be summarised as follows:

$$f_{dry} = e^{-\lambda \Sigma rain} \tag{1a}$$

$$rain_{wet} = \Sigma rain / \left(31\left(1 - f_{dry}\right)\right) \tag{1b}$$

$$P(rain > x | rain > 0) = e_{wet}^{-x/rain} \tag{1c}$$

where f_{dry} is the fraction of days without rain in a given period of 31 days (−), λ is a constant that measures the evenness of rainfall distribution (mm^{-1}), $\Sigma rain$ is total rainfall in the 31 days, $rain_{wet}$ is the average rainfall on a rainy day (mm) and $P(rain > x | rain > 0)$ is the probability that rainfall exceeds x mm on a rainy day (−).

Microclimate

Shade trees reduce day time temperature of the understorey more than they increase night time

temperature (Barradas and Fanjul 1986), which is modelled descriptively as a reduction of daily average temperature proportional to the fraction of radiation intercepted by the trees:

$$T_c = T - \Delta T(1 - e^{-k_{GR} \, LAI_t}) \qquad (2)$$

where T_c is air temperature amongst the coffee trees (°C), T is ambient temperature (°C), ΔT is the maximum reduction in daily average temperature because of shading (°C), k_{GR} is the global radiation extinction coefficient of the trees ($m^2 \, m^{-2}$) and LAI_t is tree leaf area index ($m^2 \, m^{-2}$). This empirical equation replaces detailed modelling of vertical and horizontal fluxes of heat and radiative energy through the soil–coffee–tree system.

Absolute air humidity is considered to be unaffected by shading, and therefore relative humidity increases with the lowering of temperature.

Atmospheric CO_2 concentration is considered to be unaffected by the plants and is read from input file.

Coffee growth and production

The model considers, for shaded and sunlit coffee plants separately, how carbon and nitrogen content, leaf area and phenology change over time. Seven state variables are distinguished: carbon in leaves, woody aboveground parts, roots and reproductive organs (kg C m^{-2}), nitrogen in leaves (kg N m^{-2}), LAI ($m^2 \, m^{-2}$) and phenological stage (dimensionless). The nitrogen contents of woody plant parts, roots and reproductive organs are not treated as separate state variables but are calculated from the respective carbon contents by multiplication with organ-specific N/C-ratios.

Light interception is modelled by Beer's law with a constant light extinction coefficient. Assimilate production is calculated by multiplying light interception with a light-use efficiency that decreases with light intensity:

$$LUE = \frac{\alpha}{1 + \frac{\alpha \, k \, I_0}{P_{max} \delta}} \qquad (3)$$

where LUE is canopy light-use efficiency (kg C MJ^{-1}), α is upper leaf light-use efficiency (kg C MJ^{-1}), P_{max} is upper leaf light-saturated photosynthetic rate (kg C $m^{-2} \, d^{-1}$), I_0 is incident photosynthetically active radiation (MJ $m^{-2} \, d^{-1}$), k is the light

extinction coefficient ($m^2 \, m^{-2}$) and δ is photoperiod duration (d d^{-1}). Equations for α and P_{max} are derived from the limits of the Farquhar photosynthetic rate equations (Farquhar et al. 1980) for very low and high light intensity, respectively. The derivation of the LUE-equation was described in detail by Van Oijen et al. (2004) and examples of its successful application to growth modelling of various plant species were given by Höglind et al. (2001), Van Oijen et al. (2004), Van Oijen and Ewert (1999) and Rodriguez et al. (1999). The equation yields the highest values for LUE (approaching the value of α) at low light intensity I_0. This effect is negated in models that allow respiration rate to exceed photosynthesis at low light intensity. Instead, we assume a constant ratio of daily rates of respiration and photosynthesis, which may be more generally correct (Gifford 2003; Keith et al. 1997; Malhi et al. 1999), and is consistent with high rates of photosynthesis observed at low light intensity in shade plants like coffee (Franck and Vaast 2009).

Besides being sensitive to light intensity, the calculated value of LUE depends on atmospheric CO_2 concentration and temperature, through their impact on α and P_{max} (Farquhar et al. 1980; Van Oijen et al. 2004). Further, LUE is assumed to be decreased in case of drought. This is modelled as a proportionality with the ratio of actual and potential transpiration rate (Kropff 1993), the latter being calculated by means of the Penman equation (Penman 1948). Actual transpiration rate decreases below the potential rate when soil water content drops below a critical level, which is lower than field capacity by an amount that depends inversely on atmospheric evaporative demand (Driessen 1986; Farre et al. 2000). Daily rainfall is intercepted by the foliage up to a maximum level which is proportional to LAI. The intercepted water reduces transpirational demand and evaporates the same day. Finally, growth is hampered if insufficient nitrogen is available to maintain N/C-ratios. Nitrogen uptake by the coffee plants is limited by either supply from the soil or demand by the plants. N-supply follows a Michaelis–Menten function of soil mineral N concentration, and is proportional to root biomass. N-demand is the sum of organ-specific multiplications of N/C-ratio and growth rate in terms of carbon. If N-supply becomes less than demand, allocation of N to leaves decreases until a minimum leaf N/C-ratio is reached.

Besides the effect of N-deficiency on allocation to leaves, the model assumes that the pattern of assimilate allocation to different organs is constant with four exceptions: (1) after flowering, reproductive growth gradually increases towards a maximum, returning to zero at bean maturation, (2) the maximum sink strength of reproductive growth is proportional to light intensity around flowering, (3) reproductive growth only starts in the 3rd year after planting, and is hampered for 1 year after pruning of the coffee plants, (4) allocation to roots adheres to a functional balance, increasing in case of drought and N-deficiency.

The two key phenological events in the model affecting the pattern of assimilate distribution are flowering and bean maturation. The onset of flowering was modelled as the 1st day of the year exceeding a threshold amount of rain. Bean maturation follows a fixed number of degree days later.

Leaf area increases as the product of leaf biomass growth rate and specific leaf area, the latter being reduced in case of drought. Senescence of all organs follows organ-specific time constants, and leads to the addition of carbon and nitrogen to the soil.

Trees

The submodel for trees is based on the BASic FORest simulator (BASFOR), described in more detail elsewhere (Van Oijen et al. 2005). Here we give a general overview, emphasising the differences with the submodel for the coffee plants.

Six state variables are distinguished: carbon in leaves, branches, stems and roots (kg C m^{-2}), nitrogen in leaves (kg N m^{-2}) and tree density (m^{-2}). As for the coffee plants, nitrogen contents in other organs than leaves are not treated as state variables but are calculated through fixed organ-specific N/C-ratios. All morphological variables, i.e. projected crown area of individual trees (A_c; m^2), leaf area index (LAI_t; m^2 m^{-2}), wood volume (V; m^3 m^{-2}) and tree height (h; m), are calculated as functions of the biomass variables:

$$A_c = k_{c1}\left(\frac{C_b}{d}\right)^{k_{c2}} \tag{4a}$$

$$LAI_t = \frac{C_l\,SLA_t}{Min[1, A_c d]} \tag{4b}$$

$$V = \frac{C_s}{w} \tag{4c}$$

$$h = k_{h1}\left(\frac{C_s}{d}\right)^{k_{h2}} \tag{4d}$$

where C_b, C_l and C_s are the amounts of carbon in branches, leaves and stems (kg C m^{-2}), d is tree density (m^{-2}), SLA_t is specific leaf area (m^2 kg^{-1} C), w is wood density (kg C m^{-3}) and k_{c1}, k_{c2}, k_{h1} and k_{h2} are allometric constants. The allometry was based on biomass rather than stem diameter (the common choice in forestry, Von Gadow and Hui 1999), because pruning breaks the relationship between stem and crown variables, and biomass is the primary model output. The division by tree density d in three of the four morphological equations transforms the biomass variables from area-based to individual-based.

The shaded fraction of the field (Fig. 1) is calculated as the product of individual-tree crown area and tree density ($A_c d$), capped at unity if the crowns overlap. Tree resource dynamics, i.e. light interception and transmission, nitrogen and water uptake and litter fall only apply to this shaded area. Light interception by the trees depends on LAI_t, following Beer's law, with the tree canopy always assumed to be above the coffee foliage.

Tree growth rate is calculated by multiplying light interception with a light-use efficiency (LUE_t) which is calculated more simply than the LUE of the coffee plants, not involving the Farquhar equations. LUE_t follows an optimum curve with respect to temperature and, as for coffee, decreases proportionally to the ratio of actual and Penman potential transpiration. CO_2-effects are modelled empirically using the concept of the biotic growth factor β (Gifford 1980) which assumes proportionality between growth enhancement by elevated CO_2 and the logarithm of the ratio of elevated to default atmospheric CO_2 concentration. Nitrogen relations and senescence are modelled mostly as for the coffee plants, except that leaf senescence rate may be accelerated in case of drought. Also, three of the six selected tree species fix nitrogen, at a rate proportional to root growth. Root growth is the model proxy for the true drivers of N-fixation as both are stimulated under conditions of high C-availability and high N-demand.

Allocation is modelled more simply than for the coffee plants in that no reproductive growth is simulated, obviating the need for a phenology algorithm. However, as for the coffee plants, allocation to roots increases relative to leaf allocation in case of drought or N-deficiency, and allocation to leaves also diminishes when LAI_t approaches a species-specific maximum.

Rainfall is intercepted by trees up to a species-specific maximum level proportional to LAI, leaving less water for interception by coffee plants and infiltration into soil.

Soil

The soil submodel is a simple one-layer model, of fixed depth, with eight state variables: carbon and nitrogen in litter, unstable and stable organic matter (kg C m^{-2}, kg N m^{-2}), mineral nitrogen (kg N m^{-2}) and water (kg m^{-2}, assumed equivalent to mm water). Two soil compartments of constant depth are distinguished, representing the shaded and unshaded parts of the field. The soil water, carbon and nitrogen balance equations read as follows:

$$\frac{dW_{soil}}{dt} = \text{Water gain from rainfall minus}$$
$$\text{rainfall interception}$$
$$- \text{ water loss by transpiration,}$$
$$\text{evaporation, drainage and run-off} \quad (5a)$$

$$\frac{dC_{soil}}{dt} = \text{C - gain from plant senescence,}$$
$$\text{thinning and pruning}$$
$$- \text{ C - loss from decomposition of litter}$$
$$\text{and organic matter, and in run-off} \quad (5b)$$

$$\frac{dN_{soil}}{dt} = \text{N - gain from plant senescence,}$$
$$\text{thinning, pruning, fixation and fertilisation}$$
$$- \text{ N - loss by plant uptake, emission,}$$
$$\text{leaching, and in run-off} \quad (5c)$$

where dW_{soil}/dt is the change in soil water content (kg m^{-2} d^{-1}), dC_{soil}/dt is the change in total soil carbon in litter and organic matter (kg C m^{-2} d^{-1}) and dN_{soil}/dt is the change in total soil nitrogen in litter, organic matter and mineral N (kg N m^{-2} d^{-1}).

Apart from the input of water by rain, irrigation can be simulated, although irrigation is not common in coffee agroforestry. Potential rates of transpiration and evaporation are calculated by means of the Penman formula (Penman 1948), taking into account the effect of radiation interception by the plants on partitioning of latent and sensible heat fluxes between soil and vegetation. Actual rates of transpiration depend on soil water content according to the site-specific soil water retention curve. Run-off (mm d^{-1}) is modelled as proportional to the daily rain not intercepted by the canopy (mm d^{-1}), increasing from zero on flat soil to complete run-off on vertical soil:

$$\text{Runoff} = \text{rain} \cdot \sin(s) \cdot e^{-k\,(LAI + LAI_t)} \quad (6)$$

where s (radians) is the slope of the field with respect to the horizontal, and the final exponential term is intended to capture the protective effect of coffee and tree vegetation against run-off. Variation in the sine of the slope accounts for 74% of the variance in the soil loss data reported from erosion measurements in Malaysian oil palm plantations (Hartemink 2005). Rain that is not intercepted or run-off infiltrates the soil. Drainage from soil to ground water is proportional to the amount of soil water in excess of saturation.

Carbon cascades from litter to unstable organic matter to stable organic matter, with fixed time constants and efficiencies for each conversion step, following the simple soil model developed by Goudriaan (1990) and Goudriaan and Ketner (1984). Nitrogen follows the same cascade, with some organic N being lost at each conversion step and also by the slow turnover of stable organic matter. The organic N lost contributes to the soil mineral nitrogen pool. Input to the soil pools is from aboveground litter fall, adding to the litter pool, and from root senescence, directly adding to the pool of unstable organic matter (Goudriaan 1990). The availability of N to the plant may also be increased by nitrogen fixation if the trees have that capacity. Mineral N is depleted by uptake by the coffee plants and the trees, by leaching and by emission from the soil surface. N-leaching is proportional to water drainage rate times soil mineral N concentration, the proportionality constant being less than one for soils that are still in the process of binding mineral N to soil particles. N-emission also depletes soil mineral nitrogen, at a rate that increases with the

amount of soil water. Finally, soil organic matter, including both C and N, may be lost by erosion at a rate proportional to surface water run-off. This is not modelled by means of the often used Revised Universal Soil Loss Equation (RUSLE; (Renard et al. 1991)) because information on soils is generally too limited in Central America to quantify its six parameters and default parameterisation leads to large overestimates of erosion in Central America (Vahrson 1991). Instead, we use the following equation with only one new parameter (r) to be fitted from observed rates of soil loss:

$$\text{Loss}_X = \text{Runoff} \cdot \frac{X}{h} \cdot r \qquad (7)$$

where Loss_X is the loss of C or N from soil (kg m^{-2} d^{-1}), X is soil C or N content (kg m^{-2}), h is soil depth (m) and r is the concentration ratio of C or N from litter plus unstable organic matter in run-off water to that in bulk soil ([kg kg^{-1} water] [kg m^{-3} soil]$^{-1}$). A similar enrichment factor approach was used by Starr et al. (2000) for modelling carbon loss from soils in Ohio. The division by soil depth h converts soil C or N content per unit surface area to that per unit soil volume.

Management

Various time-dependent management processes are simulated. N-fertilisation is modelled as a direct addition of mineral nitrogen to the soil. Pruning of coffee plants is modelled as removal of a specified fraction of all above-ground material. Coffee harvesting is complete removal of reproductive growth. Tree pruning is modelled as a fractional removal of foliage and branches, whereas tree thinning removes complete trees. Materials removed by pruning and thinning are assumed to add C and N to soil litter except for the roots of thinned trees which add to the unstable organic matter.

Competition between coffee plants and trees

With respect to light, the model is kept simple, with tree crowns being assumed to be higher than the coffee plants, so trees have first access to light. In contrast, there is true competition for soil water and mineral N, and the distribution of these resources between the two species depends on their relative resource demands, the relative root system densities, and the specific uptake capacities of the root systems.

Spatial dynamics

The shaded part of the field increases in size when the tree crowns expand, until the whole field is shaded. Conversely, the shaded area decreases each time trees are pruned or thinned. Because all state variables in the model are expressed with regard to either shaded or unshaded ground area, they need to be recalculated whenever the shaded area changes in size. We derived (Appendix 2) the following differential equation that keeps track of the recalculation for any state variable x:

$$\mathrm{d}x_i/\mathrm{d}t = \text{Max}[0, \mathrm{d}A_i/\mathrm{d}t/A_i] * (x_j - x_i) \qquad (8)$$

where x_i (having units of x m^{-2}) is the value of the variable in one part of the field, e.g. the shaded area A_i (m^2), and where x_j is the value in the other part. Because the model is numerically solved with a daily time step, the changes $\mathrm{d}x/\mathrm{d}t$ and $\mathrm{d}A/\mathrm{d}t$ are calculated as difference equations rather than differential equations.

Simulations and discussion

Default settings of parameters and growing conditions for simulations

A literature review of quantitative information on coffee agroforestry systems (Van Oijen et al. 2010) has shown that data availability for model parameterisation is limited—and the values that have been reported are often highly inconsistent. Neither for coffee, nor for any shade tree species, is comprehensive information available. For initial model parameterisation we thus chose where possible average values of the parameters listed by Van Oijen et al. (2010, Tables 1–3), extended with guesses for the missing parameters. In a follow-up paper, we shall examine how novel methods of model calibration using measurements of growth and production rather than of parameters directly (Van Oijen et al. 2005), can be used to infer probable values of poorly measured parameters—and perform an uncertainty analysis.

The default system we simulated was a coffee agroforestry system growing under the Turrialba

weather conditions described above, on soils with a slope of 5% and with initially 113 ton ha^{-1} carbon and 10 ton ha^{-1} nitrogen in the root zone, fertilised with 150 kg N ha^{-1} y^{-1}, and with 250 shade trees ha^{-1} (thinned to half that after 2.7 years, and annually pruned) of a generic N-fixing species with parameter values averaged over the leguminous trees listed by Van Oijen et al. (2010, Table 2). The default system thus does not represent any specific existing coffee-tree combination—trees which are average in all respects do not exist—but is chosen only to provide a reference point for assessing the impact of changes in the system. Also, we calculate all ecosystem services for each simulated system, even though in practice some services may not be provided. For example, *E. poeppigiana* does not provide timber as its wood is of low quality—but we do calculate timber yield for systems that include the species. Eight years of growth were simulated, from 1-6-1997 to 30-5-2005. We carried out three types of simulation with the model:

(1) Simulations using the default system and a system without shade trees;
(2) Simulations with one environmental factor modified or shade tree species substituted;
(3) Simulations with weather conditions of different sites in Central America.

Simulations using the default system, with and without shade trees

Predictions of the model for the default system, and a similar one without trees, are shown in Figs. 2 and 3 and in the top two rows of Table 1. The first coffee bean yield is at the end of the 3rd year, 2000 (Fig. 2). Yields then vary between years, because of changes in plants, soil and weather, averaging around 2 tons dry matter ha^{-1} y^{-1}, with about 20–30% higher yields in the full-sun system. Lower yields under shade than in full sun have been reported for Costa Rica and Brazil by Fournier (1988) and Campanha et al. (2005). Note that the yield value of 1.32 ton dry matter ha^{-1} y^{-1} given in Table 1 is the average over all 8 simulated years. Wood volume increases continuously from the start except for the thinning event after 2.7 years. Soil carbon decreases initially but stabilises when regular tree prunings—absent in the full-sun system—commence. The prunings also

cause the jagged pattern over time of tree LAI. The dry season causes a drop in soil water content early each calendar year, but overall the dry season in Turrialba is relatively mild and has little impact on coffee and tree LAI.

Figure 3 shows the soil nitrogen and water balance of the default and full-sun system. The dominant influx of nitrogen is that by fertilisation, with fixation and litter fall (including pruning) being of minor importance. The major losses of N from the soil are through leaching—28% higher in the full-sun system than in the default system, consistent with the findings of (Nair et al. 1999)—and plant uptake, with only minor volatile N-emission to the atmosphere. Kass et al. (1999) confirm that not enough N_2O is produced on shaded coffee farms to constitute a greenhouse gas problem. The simulated values of around 8 kg total N emission ha^{-1} y^{-1} compare well with reported values of 4–6 kg N_2O-N ha^{-1} y^{-1} for coffee systems in Costa Rica without and with *I. densiflora* (Hergoualc'h et al. 2008). The presence of trees in the default system increases soil N-availability, from N-fixing and litter/pruning, but N-uptake by the coffee plants is still greater in the full-sun system. The simulations of the N-cycle are qualitatively consistent with observations (Babbar and Zak 1994, 1995), but our values of N-leaching are higher than have been reported. This may be because our model does not simulate persistent storage of N by adsorption to soil particles (Reynolds-Vargas et al. 1994), but the strength of this mechanism is not well known. Alternatively, given the high fertilisation rates of coffee systems and the relatively minor removal of N in harvests, the model may have correctly identified the destination of the surplus N. Further studies of the N-cycle, where all fluxes are measured in the same system, are needed.

The use of the rain water—averaging 8.6 mm d^{-1}—is very similar in the default and full-sun systems, with interception and transpiration equalling 0.7–0.8 and 2 mm d^{-1} in both cases. Both vegetations provide sufficient soil cover to reduce direct soil evaporation to <0.2 mm d^{-1}. The largest flux by far is that of drainage to the ground-water. Run-off is of small importance because of the small slope angle of 5%. The simulations of the water cycle compare well with the results reported by Van Kanten (2003), who found average coffee transpiration to be less than 1 mm d^{-1} in full sun and under shade of *E. deglupta*,
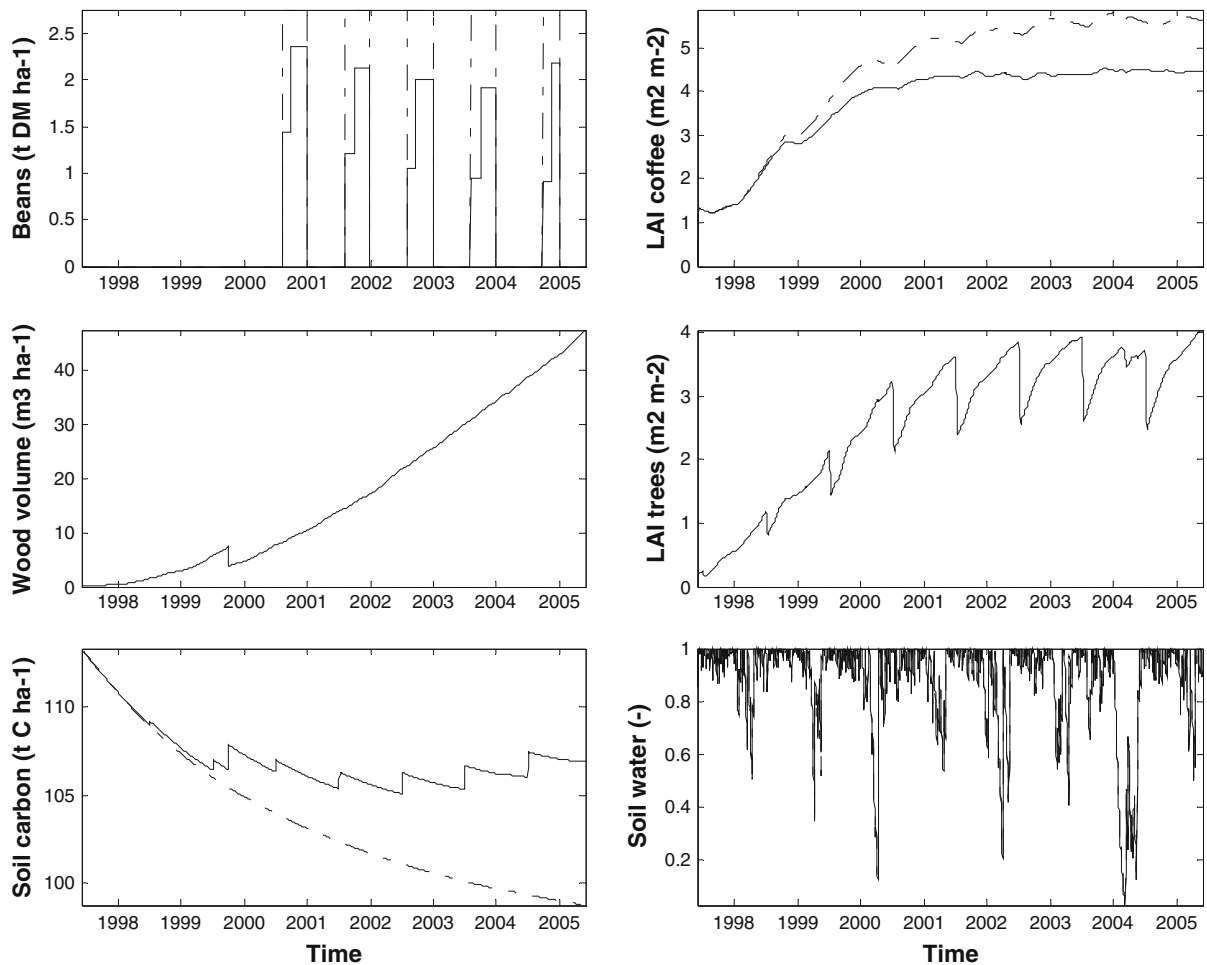
Fig. 2 Default simulations of plant and soil dynamics. *Continuous lines*: agroforestry system with coffee grown under 250 trees ha^{-1} of a generic N-fixing shade tree species under climatic and soil conditions as in Turrialba, Costa Rica. *Dashed lines*: same conditions but without trees (full sun system)

E. poeppigiana and *T. ivorensis*, with the trees transpiring at 0.9–2.1 mm d^{-1}. Imbach et al. (1989) also found that the largest water flux was that of drainage, at 50–60% of the total in coffee with *C. alliodora* and *E. poeppigiana*.

The full-sun system allows greater coffee yields, but all other indicators are worse: there is no wood production, carbon sequestration is reduced, and losses of N and of soil are increased (Table 1).

Simulations with one environmental factor modified

Besides the default system, we carried out 20 simulations in which each time one different factor was varied (Table 1). Six of these simulations replaced the

default generic shade tree with one of the six target species of the study (*C. alliodora*, *E. poeppigiana*, *E. deglupta*, *G. sepium*, *I. densiflora*, *T. ivorensis*). As explained in Sect. "Simulations and discussion", we do not have full information on the differences between these species, so we only had species-specific parameterisation for wood density, leaf senescence rate, leaf nitrogen content, tree allometry, SLA, light extinction coefficient and whether the trees were N-fixing or not (but all three N-fixers having the same N-fixation capacity). With these species differences, *G. sepium* growth was poorest whereas *E. poeppigiana* and *T. ivorensis* grew best, with only *T. ivorensis* having a major negative impact on coffee growth (Table 1). Van Kanten (2003) also found that *T. ivorensis* reduced coffee yield considerably more than
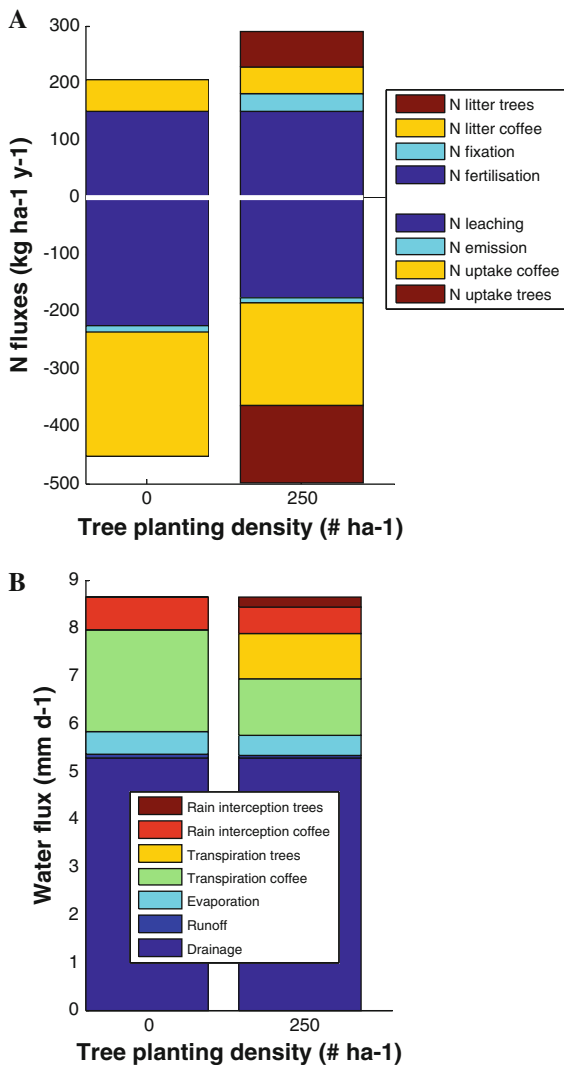
Fig. 3 Average fluxes of nitrogen and water in the default simulations for a coffee agroforestry system (*right columns*) and a full-sun system without trees (*left columns*). **a** Soil nitrogen balance, inputs to the soil shown above the mid-line and outputs below. **b** Water budget, showing how rain water is used in the system

E. peoppigiana and *E. deglupta* did. C-sequestration was highest with the two fastest growing species and with *I. densiflora*. The three N-fixing species caused higher rates of N-leaching and N-emission than the non-N fixers.

Tree management aimed at restricting shade levels (lower tree density, an extra thinning event, twice yearly pruning) all increased coffee yield but at the expense of wood production and with higher losses of N and soil. Beer (1992) found that coffee yields

increased by 30% when reducing the density of *C. alliodora* from 260 to 100 ha^{-1}. Beer et al. (1997), in a literature review, also found that runoff and soil loss tend to be higher in full sun systems. A 100% increase in N-fertilisation had little impact on the simulations apart from a small increase in wood production (10%), and a major increase in the N-loss fluxes (about 70%).

Moving the system to a steeper slope (of 50%) only affected the loss of soil markedly—sevenfold, but the erosion level is still minor, consistent with findings by Vahrson (1991). Other environmental changes had more impact. Rain fall proved very influential, and the simulations suggest that the amount of rain in the Turrialba area is at the upper range of what the system can handle. Doubling of rain fall intensity hampered production and C-sequestration, and caused higher losses of N and soil. Perhaps surprisingly, increased rain fall reduced N-emission from the soil, even though the soil was more water-saturated. This effect was due to the extra flow of water through the system reducing the concentration of mineral N in the soil. The response to temperature change was less unequivocal, with the trees better able to handle 5°C warming than the coffee plants. Finally, the impact of doubling atmospheric CO_2 concentration was found to be the only change that was beneficial on all accounts: increased coffee and tree production and C-sequestration with lower losses of N and soil. An additional simulation showed that at the doubled CO_2 concentration, higher N-fertilisation rates could be justified. For most of these changes in environmental factors, no literature could be found to compare with the simulations.

Simulations with weather conditions of different sites in Central America

To more closely examine the importance of differences in weather, we ran the model for the 24 Central American sites above 600 m altitude in the FAOC-LIM weather database (Van Oijen et al. 2010). The sites differ in all weather variables: temperature, radiation, rain, wind, humidity. Monthly rain data were converted to daily values using the rain fall generator described in Appendix 1. All parameter settings for coffee, trees and soil were maintained as in the default system, so these simulations do not

Table 1 Simulations exploring the effects of single-factor changes in coffee agroforestry systems on annual average yield (coffee bean production, wood volume production) and environmental impact (C-sequestration on-site, water drainage, N-leaching, volatile N-emission and soil C-loss in runoff)

Variable	Coffee production	Wood production	C-sequestration	Water drainage	N-leaching	N-emission	Soil C loss
Default system	1.32 t DM ha⁻¹ y⁻¹	6.37 m³ ha⁻¹ y⁻¹	3.81 t C ha⁻¹ y⁻¹	5.28 mm d⁻¹	175.34 kg N ha⁻¹ y⁻¹	8.02 kg N ha⁻¹ y⁻¹	0.07 t C ha⁻¹ y⁻¹
% Change relative to default system							
Full sun system (no shade trees)	29	−100	−54	0	28	27	16
C. alliodora	−6	5	0	−1	−18	−17	−2
E. deglupta	−8	2	10	1	−15	−15	3
E. poeppigiana	−16	112	15	1	−12	−12	−2
G. sepium	26	−70	−35	−2	16	17	5
I. densiflora	−6	24	15	−1	0	0	−9
T. ivorensis	−57	102	29	4	−16	−16	−6
Tree density × 2	−48	88	35	3	−15	−15	−11
Extra tree thinning	6	−25	−16	0	8	8	5
Tree pruning freq. × 2	13	−32	−19	1	7	7	8
Coffee pruning	−26	0	−22	1	13	12	57
No fertilisation	−22	−30	−46	1	−46	−49	53
Fertilisation × 2	1	10	13	−1	69	70	−13
Slope = 0%	0	0	1	1	1	0	−100
Slope = 50%	−1	2	−7	−7	−7	4	714
Rain × 0.5	−2	9	13	−78	−28	164	−62
Rain × 2	−28	−35	−70	162	50	−38	336
Temperature −5°C	17	−5	−20	5	11	8	14
Temperature +5°C	−19	−31	−10	14	7	−2	1
[CO₂] × 2	20	32	51	0	−30	−28	−10

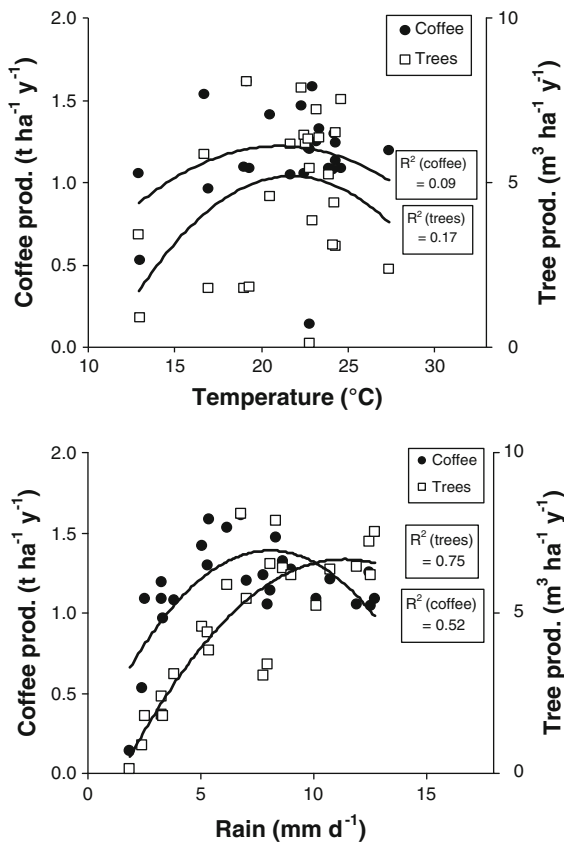The default system and the full sun system are the same as in Fig. 2

Fig. 4 Simulations for the default coffee agroforestry system across 24 sites in Central America, using site-specific weather data from the FAOCLIM database

provide a complete characterisation of true site differences. The simulations generated widely varying coffee and tree yields for the 24 sites, with differences in temperature and rain being the two major drivers (Fig. 4). The simulations suggest that optimal values of temperature and rain are 18–25°C and 5–10 mm d^{-1}, with more sites being too dry for tree growth than for coffee growth. Amaral et al. (2001) cited the work of Nunes et al. (1968), who reported a 10% reduction in dry matter production of coffee per degree above 24°C under controlled conditions, but they did not find clear effects of temperature themselves.

Evaluation of model quality and data availability

Compared to crop modelling, agroforestry modelling is still in its infancy. The model presented in this

paper is one of the first that simulates a tropical agroforestry system. The model simulates the mass balance of carbon, nitrogen and water fluxes through a coffee agroforestry system. The model is kept simple because, as the literature review showed, there is insufficient empirical information available for building a complex parameter-rich model. Furthermore, model simplicity enhances the chances that it will ultimately become useful in decision-making—and not remain purely a research tool like most models developed for tropical systems (Matthews et al. 2000). As indicated in the previous paragraphs, model behaviour is generally consistent with the available literature, which, however, is not extensive.

The simplicity of the model does imply that the model is not responsive to various environmental factors known to play a role in managed ecosystems, such as weeds, pests and diseases, and deficiencies or excesses of other elements than nitrogen. However, the importance of these factors in coffee agroforestry is not altogether clear, whereas the model is responsive to factors of known importance such as shade tree species choice and management, coffee management, weather and soil conditions including nitrogen availability.

The model also has limitations in that it does not produce results for some important indicators of the success of coffee agroforestry systems, such as the quality of coffee beans and tree timber, and the impact of management decisions on biodiversity (Dix et al. 1999). However, the model is complex enough to permit preliminary assessment of the trade-offs between increasing coffee and tree productivity, and between maximising productivity and limiting the impact of the system on the environment.

For systems with shade trees, the model subdivides space into two parts: the shaded and not shaded area of the field. This is done dynamically, with the shaded area increasing with tree crown growth and decreasing with tree pruning (Fig. 1). A simpler model could be envisaged, where only one area is distinguished with a shade level equal to the whole-field average. Alternatively, space could have been subdivided into a fine grid of cells differing in tree cover. Our model is a compromise between these two extremes. The grid cell approach seemed unfeasible given the scarcity of information about the horizontal distribution of crowns and root systems (Van Oijen et al. 2010). However, the single-area approach was

possible and we investigated the sensitivity of our model to that assumption by modifying the shade projection of the trees. By assuming that shade projects onto double the crown-covered area, most of the field was shaded most of the time, in effect reducing our model to the single-area option. This choice led to a 25% increase in simulated coffee yield because no parts of the field were too warm or too dark. Data are lacking to decide whether spatial heterogeneity may be ignored in this way, but the simulations do suggest that it is better to have many closely spaced well-pruned trees than a few trees with dense foliage.

A phenomenon that is not reproduced by our simulations (Fig. 2) is that of biennial growth (Cannell 1985), which is the alternation of years with high and low bean production, possibly arising from competition between reproductive and foliar growth. However, the phenomenon has only been demonstrated convincingly at the level of individual plants and we were unable to find any publication showing whole-field yield oscillation. Even coffee fields without shade trees are often not homogeneous because different rows are pruned each year, which might obscure biennial growth patterns of individual plants. Our model only simulated a biennial pattern if we intensified the effect of reproductive growth on foliage beyond competition for resources to actual acceleration of leaf senescence. Without any evidence that biennial growth is important at the field-scale, it seemed prudent not to complicate the model with this hypothetical mechanism.

At this stage in model development, a greater weakness than that of model simplicity probably is that of limited model testing against data. In this paper, we showed various examples of how the qualitative behaviour of the model is in accordance with observations, but a rigorous test against detailed data has not been performed, nor has the uncertainty of model outputs been quantified.

Conclusions and outlook

Given the limited information available on coffee and trees, only preliminary parameterisation of the model developed here was possible. However, as indicated at various places in the previous section, model behaviour seemed qualitatively consistent with the literature on system productivity and the nitrogen and water balance. The main preliminary conclusions we might draw from the simulation results summarised in Table 1 and Figs. 3–4 are the following:

Productivity and management

- Given that our simulation used typical or even low values of fertilisation rate (Aguilar et al. 2001; Ramirez 1993; Ryan et al. 2001), coffee in Central America is generally overfertilised. The model results show that reduction in fertilisation is generally possible without significant impact on yield.
- N-fertilisation may be more beneficial to tree wood volume production than to coffee yield.
- Coffee yield tends to decrease with tree density, even if the trees are N-fixers. Tree pruning tends to benefit coffee productivity but with some decrease in tree productivity.
- In a comparison of six tree species, the N-fixers *E. poeppigiana*, *G. sepium* and *I. densiflora*, and the non-N fixers *C. alliodora*, *E. deglupta* and *T. ivorensis*, the simulations identified *E. poeppigiana* and *T. ivorensis* as the species producing most wood (but note that the wood of *E. poeppigiana* is considered to be of little economic value), with only *T. ivorensis* significantly hampering the growth of the coffee plants.

Biogeochemistry and impact on the environment

- The degree of N-leaching is very high in coffee agroforestry systems and this is difficult to change through any management activity other than reducing N-fertilisation.
- The rate of N-fixation by leguminous trees is generally only a minor flux in the overall N-budget of the system, but large enough to have a noticeable impact on productivity.
- The contribution of coffee agroforestry systems to greenhouse gas production in the form of gaseous N-emission is low, even at high levels of N-fertilisation.

- Carbon sequestration rates in coffee agroforestry systems are not very high and are relatively insensitive to management choices.
- Drainage of water to the groundwater is very high in the systems, and only marginally smaller at sites with steep slopes—where runoff rates are higher than elsewhere.
- Soil loss increases with slope, but generally remains of minor importance. High fertilisation levels are of benefit as they guarantee large, protective ground cover. Tree pruning decreases ground cover and is likely to increase soil loss rates but not to very high levels.

Impact of global change

- The expected future increase in atmospheric CO_2 concentration is likely to make N-fertilisation slightly more effective.
- Global warming, as calculated using the HadCM3 Global Climate Model, is expected to increase temperatures in Central America by 3.3–4.4°C in this century (Johns et al. 2003). Our simulations of the impact of 5°C warming suggest that this may decrease coffee yields significantly.
- Global warming is likely to hamper shade tree growth.

Until more data are collected for model parameterisation and testing, this list of preliminary conclusions may best be treated as working hypotheses. However, our simulations do suggest that the balance between productivity and environmental impact of coffee agroforestry systems in Central America can be altered in many different ways—and a process-based model can help make the various trade-offs transparent. Follow-up papers will focus on uncertainty analysis using data from new field experiments in Nicaragua, and on application of the model to management optimisation in the Turrialba region of Costa Rica.

Appendix 1. Rainfall generator for Central America

This appendix describes an algorithm for generating time series of daily rainfall from monthly total rainfall. The following figure shows the results of 365 consecutive daily rainfall measurements at Heredia, Costa Rica (10.03°N, 84.14°W, 1180 m altitude), from 1 April 2003 to 31 March 2004:
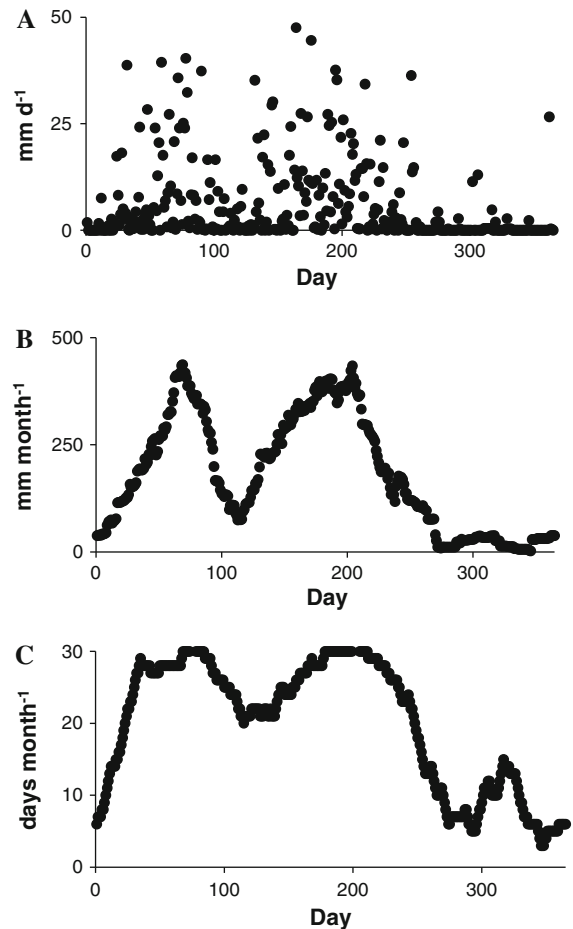
The figure shows: (a) daily rainfall, (b) the 31-day moving average, (c) the 31-day moving total of rainy days. Average daily rainfall was 5.4 mm with a standard deviation of 9.3 mm, and the total number of rainy days (rain > 0) was 242. Nonlinear regression of (c) on (b) leads to an exponential relation ($r^2 = 0.90$) for the fraction of days without rain as a function of monthly total rainfall:

$$f_{dry} = e^{-0.0087 \Sigma rain} \tag{A1}$$

where f_{dry} is the fraction of days without rain in a given period of 31 days ($-$) and $\Sigma rain$ is total rainfall in the 31 days. The amount of rainfall on rainy days follows a nearly exponential distribution with the following cumulative density function:

$$P(rain < x) = 1 - e^{-x/rain_{wet}} \tag{A2}$$

where P is the probability that rainfall is less than x mm on a given rainy day and $rain_{wet}$ is the average rainfall on a rainy day (mm), calculated as:

$$rain_{wet} = \Sigma rain / (31(1 - f_{dry})). \tag{A3}$$

These equations can be turned into a 5-step algorithm for generating daily rainfall amounts from monthly data: (1) Interpolate the monthly rainfall data to generate a day-by-day time series, (2) Calculate the corresponding time series of f_{dry} using Eq. A1, (3) For each day, assume it is dry if a randomly chosen number between 0 and 1 is less than f_{dry}, (4) For the remaining days calculate the expectation value of rain using A3, (5) For each rainy day, estimate the amount of rain as the expectation value times minus the logarithm of a randomly chosen number between 0 and 1.

Because the algorithm is stochastic it does not reproduce any observed rain data exactly. However, over 90% of generated time series for the Heredia site, matched the observed mean and standard deviation of daily rain fall, and the number of rainy days in the year, within 5, 10 and 5%, respectively. The effectiveness of the algorithm was further verified using the rainfall data from the Turrialba site.

Appendix 2. Spatial dynamics: updating variables when the shaded area changes

In agroforestry systems, the fraction of the field shaded by trees increases when the tree crowns expand and decreases when the trees are pruned or thinned. In our model, the spatial dynamics of shade require that the values of the state variables are continuously updated. The state variables in the model are all expressed per unit shaded or unshaded surface area. When area changes from unshaded to shaded, or vice versa, the state variables in the expanding part of the field become "mixed" with the corresponding variables in the other part. Say A_1 and A_2 are the sun- and shade-areas, X_1 and X_2 are *totals* of any state variable in these areas, and x_1 and x_2 are the values of the state variable per unit area ($x_i = X_i/A_i$). For example, X and x may be coffee biomass (kg) and coffee biomass density (kg m^{-2}), respectively. Then, the following statement from calculus applies:

$$dx_i/dt = d(X_i/A_i)/dt = (A_i dX_i/dt - X_i dA_i/dt)/A_i^2$$

If all changes in the x_i are due to changes in shaded area, we can eliminate the X_i and rewrite the statement in terms of x_i and A_i only:

$$dx_i/dt = Max[0, dA_i/dt/A_i] * (x_j - x_i)$$

where x_j is the state variable density in the part of the field complementary to x_i. If the x_i also change because of processes *within* the two areas (e.g. coffee growth or senescence), we add terms for those processes to the above formula for dx_i/dt.

The above formula thus affords an easy means of keeping track of changes in state variables in any agroforestry model where two types of ground cover are distinguished.

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