Plot-scale modelling of coffee agroforestry systems in Central America

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Abstract

The productivity and environmental impact of coffee agroforestry systems depends on many factors: environment, management, coffee cultivar, tree species. We present a simple dynamic model of coffee agroforestry systems that can help analyse the impacts of the different factors (van Oijen et al. 2008). The model includes the physiology 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. The model can simulate management treatments such as spacing, thinning, pruning and fertilising. Model outputs are the variables that we want the model to calculate, as a function of the inputs. The major outputs of the model are:

- **Productivity: coffee bean yield, 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.**

We analysed to what extent the literature has sufficient information to allow parameterisation of the model for various coffee-tree combinations. Information on weather,

coffee and trees is found to be limited, but soil information seems adequate. In particular missing are multi-factorial experiments to examine interactive effects of different environmental factors. Although model parameterisation thus remains uncertain, 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.

Resumen en español

Modelaje de sistemas agroforestales a escala de parcela en América Central

La productividad y el impacto ambiental de los sistemas agroforestales de café dependen de muchos factores: ambiente, manejo, plantación de café, especies arbóreas. Presentamos un modelo dinámico de sistema agroforestal de café que puede ayudar a analizar los impactos de los diferentes factores (van Oijen et al. 2008). El modelo incluye la fisiología de las plantas de café, y su respuesta a las condiciones de crecimiento diferentes. Esto es integrado dentro de un modelo de café y árboles de sombra a nivel de parcela el cual incluye la competición por luz, agua y nutrientes. El modelo puede simular tratamientos de manejo tales como espaciamiento, raleo, poda y fertilización. Los resultados del modelo son las variables que queremos que el modelo calcule, como una función de los insumos. Los resultados mayores del modelo son:

- Productividad: producción del grano de café, volumen del tronco de los árboles;
- Impacto ambiental: tasa de lixivación de N al agua subterránea y de emisión de N a la atmósfera, tasa de pérdida de carbono orgánico y nitrógeno en la escorrentía de la superficie.

Analizamos hasta qué alcance la literatura tiene suficiente información para permitir la parametrización del modelo para varias combinaciones de café-árbol. La información sobre clima, café y árboles es limitada, pero la información sobre suelo parece ser adecuada. En particular hacen falta experimentos de factores múltiples para examinar los efectos interactivos de los diferentes factores ambientales. Aunque la parametrización del modelo permanece incierta, el comportamiento del modelo parece ser consistente con observaciones. Demostramos ejemplos de cómo el modelo puede ser usado para examinar ventajas y desventajas entre el incremento de las productividades de café y de los árboles, y entre la maximización de la productividad y la limitación del impacto del sistema sobre el ambiente.

Introduction

Coffee (*Coffea arabica*, L.) poses many demands to its growing environment (DaMatta et al. 2003). For example, coffee is intolerant to frost but also to overly high temperature. Protection against both temperature extremes can be afforded by the use of shade trees.

One way of integrating the scattered knowledge on coffee agroforestry systems, is by trying to build a process-based model. Here, we describe such a model for coffee agroforestry systems that was developed in project CASCA (van Oijen et al. 2008). The purpose of the model is to explore the system's 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 was built to simulate a full rotation of coffee growth, which takes typically 10-25 years in Central America.

Here, we take the view that model complexity should be commensurate with data availability. We therefore aim for a simple coffee agroforestry 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.

A dynamic model for coffee agroforestry systems

The main components and interactions in coffee agroforestry systems that need to be modelled are shown in Fig. 1. 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.

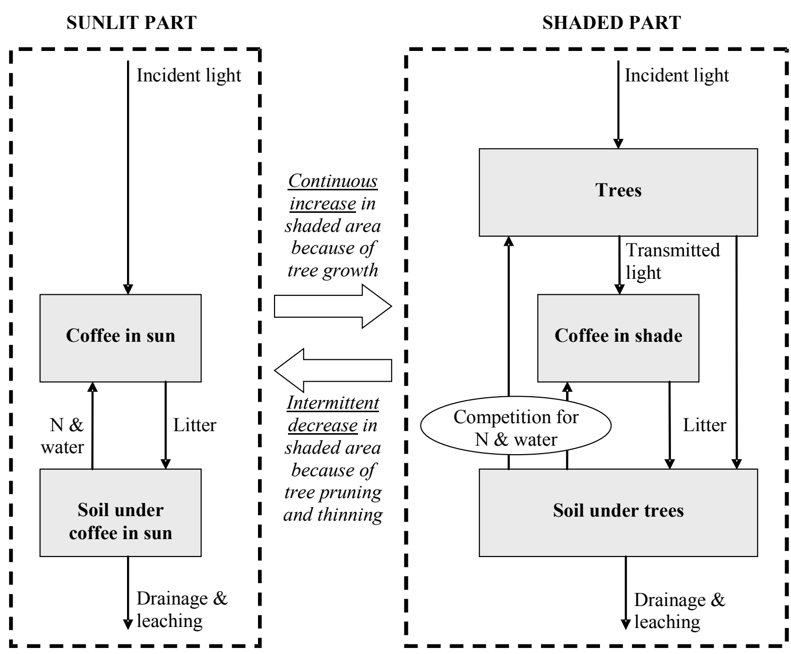

Figure 1: Resource fluxes in coffee agroforestry systems.
When tree cover is less than 100%, part of the field is not shaded (left) and competition for resources only takes place in the shaded part (right). The shaded part expands because of tree growth and contracts because of tree management.

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. There is full competition for soil resources because the root systems of the two plant types at least partly occupy the same soil volume. Tree cover is generally not 100%, so part of the field is unshaded. Our model represents both the shaded and unshaded parts of the field, and how their relative areas change over time.

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.

The inputs to the model are all the factors whose impact we want to know about:

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

For the modelling, we selected the following group of six shade-tree species that are commonly used and for which data are becoming available from various ongoing research programmes in the area: *Cordia alliodora*, *Erythrina poeppigiana, Eucalyptus deglupta, Gliricidia sepium, Inga densiflora, Terminalia ivorensis*. Besides providing shade, *E. poeppigiana*, *G. sepium* and *I. densiflora* fix nitrogen, while *Cordia alliodora*, *E. deglupta* and *T. ivorensis* provide timber.

Model outputs are the variables that we want the model to calculate, as a function of the inputs. The major outputs of the model are:

- Productivity: coffee bean yield, 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.

The model operates on a daily time step and takes as input daily values of weather conditions: radiation, temperature, precipitation, humidity and wind speed. Shade trees reduce photoperiod 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.

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 parts, roots and reproductive organs, nitrogen in leaves, LAI and phenological stage.

Light interception is modelled using 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.

The relative allocation of assimilates to different organs is constant with four exceptions: (1) after flowering, reproductive growth 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 third year after planting, and is hampered for one year after pruning of the coffee plants, (4) allocation to roots follows a functional balance, increasing in case of drought and N-deficiency.

The onset of flowering was modelled as the first 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.

The submodel for trees is based on the BASic FORest simulator (BASFOR), described in more detail elsewhere (Van Oijen et al. 2005). Six state variables are distinguished: carbon in leaves, branches, stems and roots, nitrogen in leaves and tree density. All morphological variables, i.e. projected crown area of individual trees, leaf area index (LAI_t), wood volume and tree height, are calculated as allometric functions of the biomass variables.

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, mineral nitrogen and water. Two soil compartments of constant depth are distinguished, representing the shaded and unshaded parts of the field.
Potential rates of transpiration and evaporation are calculated by means of the Penman formula (Penman 1948). Actual rates of transpiration depend on soil water content according to the site-specific soil water retention curve. Run-off is modelled as proportional to the daily rain not intercepted by the canopy, increasing from zero on flat soil to complete run-off on vertical soil.
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; Goudriaan and Ketner 1984). Nitrogen follows the same cascade.

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.

Literature review on coffee agroforestry systems

The model described above has about 60 parameters whose values need to be quantified. We searched the literature for quantitative information on the ecological and physiological processes that underlie coffee and tree productivity in coffee agroforestry systems. Literature search was conducted for the peer-reviewed literature using Web-of-Science and for the grey literature using Google Scholar and further web search. Special attention was given to publications from Central America.

Simulations

The default system we simulated was a coffee agroforestry system growing under the measured Turrialba weather conditions, 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 in the literature review. Eight years of growth were simulated, from 1-6-1997 to 30-5-2005. We carried out four types of simulation with the model:

(1) Simulations using the default system;
(2) Simulations using a system without shade trees (full sun);
(3) Simulations using different species of shade trees;
(4) Simulations with one environmental factor modified;

A summary of the predictions of the model for these various systems is shown in Table 1.

Discussion

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).

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.

At this stage in model development, a greater weakness than that of model simplicity probably is that of limited model testing against data. A rigorous test against detailed data has not been performed, nor has the uncertainty of model outputs been quantified. Based on our literature review on coffee, tree and soil parameters, we suggest that the following kinds of missing data may be needed in particular to allow model improvement:

(1) More and longer time series of daily weather data in different coffee growing regions. The FAO dataset only has monthly data for a very small number of sites.

(2) More long-term experiments that follow seasonal and inter-annual changes in coffee and trees, rather than one-off observations. Measurements over the whole rotation period, 10-25 years, would be valuable for analysing the lower yields in the first and last years. Such measurements may also help address the issue of biennial yield performance of coffee.

(3) Soil measurements that extend to greater depths than the top 10 or 20 cm.

(4) Closed-balance studies for carbon, nitrogen and water which allow quantification of the full flux-budgets without the need for guesses regarding missing fluxes.
(5) Data from multi-factorial experiments. Of particular value would be a systematic comparison of the same major shade-tree species, planted on a range of sites across Central America differing in soil and climate, with additional differences in management.
(6) Measurements on the impact of pruning on tree morphology.

Conclusions

The literature study in this paper revealed substantial quantitative information about coffee agroforestry systems in Central America, but with many gaps and inconsistencies. This allowed only preliminary parameterisation of the model developed here, but model behaviour seemed qualitatively consistent with empirical knowledge. The main preliminary conclusions from model application were:

1. Coffee in Central America is overfertilised at present: reduction in fertilization is generally possible without significant impact on yield;
2. 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-fertilization;
3. N-fertilization may be more beneficial to tree wood volume production than to coffee yield;
4. The expected future increase in atmospheric CO_2 concentration is likely to make N-fertilization slightly more effective;
5. Global warming, as calculated using the HadCM3 Global Climate Model, is expected to increase temperatures in Central America by 3.3-4.4 ºC in this century. This level of warming is expected to decrease coffee yields significantly;
6. Global warming is likely to hamper shade tree growth;

7. 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;
8. In a comparison of six tree species, the N-fixers *Erythrina poeppigiana*, *Gliricidia sepium* and *Inga densiflora*, and the non-N fixers *Cordia alliodora*, *Eucalyptus deglupta* and *Terminalia 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;
9. 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 maintain productivity;
10. 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-fertilization;
11. Carbon sequestration rates in coffee agroforestry systems are not very high and are relatively insensitive to management choices;
12. 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;
13. Soil loss in Central America is less than in other tropical regions. High fertilization levels are of benefit in this respect 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.

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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). All changes are relative to a default system with coffee grown under 250 trees ha^{-1} of a generic N-fixing shade tree species in the climate and soil conditions of Turrialba, Costa Rica.

VARIABLE	Coffee prod.	Wood prod.	C-sequestr.	Water drainage	N-leaching	N-emission	Soil C loss
Default system	1.32 t DM ha^{-1} y^{-1}	6.37 m^3 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
Cordia alliodora	-6	5	0	-1	-18	-17	-2
Eucalyptus degluptans	-8	2	10	1	-15	-15	3
Erythrina poeppigiana	-16	112	15	1	-12	-12	-2
Gliricidia sepium	26	-70	-35	-2	16	17	5
Inga densiflora	-6	24	15	-1	0	0	-9
Terminalia ivorensis	-57	102	29	4	-16	-16	-6
Tree density x 2	-48	88	35	3	-15	-15	-11
Extra tree thinning	6	-25	-16	0	8	8	5
Tree pruning freq. x 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 x 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 x 0.5	-2	9	13	-78	-28	164	-62
Rain x 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
$[CO_2]$ x 2	20	32	51	0	-30	-28	-10