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# DESIGN OF CROPPING SYSTEMS COMBINING PRODUCTION AND ECOSYSTEM SERVICES: DEVELOPING A METHODOLOGY COMBINING NUMERICAL MODELING AND PARTICIPATION OF FARMERS.

**Application to coffee-based agroforestry in Costa Rica.**


Présentée et soutenue publiquement par

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# SUMMARY

In the face of increasing concerns about sustainability of agricultural production, cropping systems are evolving towards systems that fulfill multiple agronomic and environmental objectives. Research in cropping systems design (CSD) is concerned with studying the effect of farming practices on cropping systems and their performance. The interaction between production and other ecosystem services, and quantification of trade-offs between them, is a key aspect of this research. A variety of approaches have been theorized, such as use of models and mobilization of expert knowledge. Models allows fast and low-cost testing of the effect of farming practices under a variety of conditions, but the application of theoretical outcomes to on-farm changes can be limited by local constraints and researcher-farmer communication. Mobilizing farmers and other relevant stakeholders for CSD can help overcome these obstacles; however this limits innovation to the scope of expert knowledge.

The objective of this thesis is to combine modeling and participatory approach for a CSD methodology that harnesses the potential of numerical modeling while ensuring the proposed solutions take into account farmers' constraints and opportunities. After an overview of current advances in prototyping and CSD, we propose an methodological framework divided into four parts; a) combining a typology of farming practices and a conceptual model to appraise the diversity of farming practices, constraints and trade-offs at the plot scale in a defined production area; b) collection of field data for quantifying relevant trade-offs between production and ecosystem services; c) selecting and preparing an appropriate numerical model for simulating the effects of farming practices on production and provision of ecosystem services; and d) evaluating whether the interaction of farmers with a numerical model can generate candidate cropping systems that fulfill our agro-environmental objectives (provision of ecosystem service) as well as being suitable for the farmers who will adapt them for on-farm experimentation.

The coffee-based agroforestry systems (coffee/shade trees) of central Costa Rica were the chosen production system for answering these questions. Agroforestry systems offer plentiful opportunities for valuing ecosystem services in addition to crop production; the combination of two perennial crops brings long-term performance assessment and sustainability of the system to the heart of the question. Coffee cultivation in central Costa Rica concerns a large amount of livelihoods, but is also based on intensive management of a highly valued cash crop vulnerable to price fluctuations on the global market as well as climate change. Steep slopes and heavy rainfall also cause high levels of soil erosion; yet certain indirect erosion control practices (such as the use of shade trees of weeds) also have an impact on coffee production. The reconciliation of these two aspects offers the opportunity to test our methodological framework in situations where precise discussions on production/environment trade-offs are needed.

Finally, in the last chapter we reflect on the importance of correctly choosing and preparing the right model for the job, potential application of this methodology, as well as the recommendations were able to make in terms of erosion control practices in the study area.

# RESUME

Face aux besoins croissants pour une production agricole durable, les systèmes de culture évoluent vers des systèmes qui accomplissent des objectifs environnementaux et agricoles multiples. La recherche en conception de systèmes de cultures (CSC) s'intéresse à l'effet des pratiques et de l'environnement sur les systèmes de culture et leur performance. L'interaction entre production et services ecosystémiques, et la quantification de ces relations, sont un aspect clé de ce domaine de recherche. Une variété d'approches ont été théorisées, tels que l'utilisation de modèles et la mobilisation de connaissances expertes. Les modèles permettent de tester rapidement et à faible coût l'effet de pratiques agricoles dans une variété de conditions, mais l'application de conclusions théoriques à la parcelle peut être limitée par des contraintes locales ainsi que des obstacles à la communication chercheur-agriculteur. Mobiliser les agriculteurs et autres acteurs pertinents pour la CSC peut aider à surmonter ces obstacles ; cependant, cela limite l'innovation au cadre des connaissances expertes. L'objectif de cette thèse est de combiner la modélisation et des méthodes participatives pour une méthode de CSC qui exploite le potentiel de la modélisation numérique tout en s'assurant que les solutions proposées prennent en compte les contraintes environnementales et socioéconomiques. Après avoir revu l'état d'avancement de la recherche en prototypage et en CSC, nous proposons un cadre méthodologique divisé en quatre parties ; a) combiner une typologie des pratiques et un modèle conceptuel pour évaluer la diversité des pratiques, contraintes et trade-offs dans une zone de production ; b) acquérir des données de terrain pour quantifier les trade-offs pertinents entre production et services écosystémiques ; c) sélectionner et préparer un modèle numérique approprié pour simuler les effets des pratiques sur la production et l'apport de services ; et d) évaluer si l'interaction d'agriculteurs avec le modèle numérique peut générer des systèmes de culture potentiels qui répondraient aux objectifs agro-environnementaux posées (apport d'un service écosystémique) ainsi qu'être acceptables pour les agriculteurs qui les adapteraient à l'expérimentation dans leurs parcelles. The systèmes agroforestiers à base de café (cafés/arbres d'ombrage) du Costa Rica central ont étés le système de culture choisi pour répondre à ces questions. Les systèmes agroforestiers offrent de nombreuses occasions d'étudier et évaluer les services écosystémiques apportés, en plus de la production principale. L'association de deux cultures pérennes place l'évaluation de la performance à long terme et de la durabilité des systèmes au centre de la question. La culture du café au Costa Rica fait vivre une part importante de la population, et est aussi basée sur la gestion intensive d'une culture à haute valeur d'exportation, vulnérable aux fluctuations des prix sur le marché mondial ainsi qu'au changements climatiques. Des pentes raides et une saison des pluies importante créent des problèmes d'érosion significatifs ; cependant, certaines pratiques de contrôle de l'érosion (utilisation d'arbres d'ombrage et d'adventices) impactent la production de café. La réconciliation de ces deux aspects nous offrent l'occasion de tester notre cadre méthodologique dans une situation où une solide argumentation technique serait nécessaire pour encourager les expérimentations dans les parcelles. Enfin, le dernier chapitre porte une réflexion d'ensemble sur l'importance de choisir et préparer correctement un modèle agronomique adéquat, les applications potentielles de cette méthodologie, ainsi que les recommandations que nous avons pu effectuer en termes de pratiques de contrôle de l'érosion dans la zone d'étude.

# CHAPTER 1

# SCIENTIFIC CONTEXT AND THESIS OBJECTIVES

## 1.1 CURRENT ADVANCES IN PROTOTYPING AND CROPPING SYSTEM DESIGN

### *1.1.1 NEED FOR CROPPING SYSTEM DESIGN AND SYSTEMIC APPROACH*

During the past century, expansion of farm and pasturelands as well as increased mechanization and use of agrochemicals have exacerbated the effect of agricultural practices on the natural environment (Edwards and Wali, 1993; (MEA), 2005). Human populations have also been affected, at the local scale by erosion and pollution of land and water systems, and at the global scale by the increase in greenhouse gas emissions of intensive agriculture (Johnson *et al.*, 2007). As the realization of this fact takes hold of the global conscience, pressure on farmers is increasing to improve the environmental performance of the agro-systems they manage.

At the same time, the sustainability of farming operations themselves is put into question. Farmers are ever more vulnerable to global changes in the climate and in international markets (Leichenko and O'Brien, 2002). Changes in weather patterns and in frequency of extreme climatic events, and changes in the sale prices of produce as well as agrochemicals, create a need for rapid responsiveness of farmers to adapt their management to these changes.

Farms therefore need to respond more and more to **multiple performance requirements**. Production remains a key function, but has to be combined with other assessment criteria (Bockstaller *et al.*, 2009).

Cropping system design (CSD) involves conceptualizing the agro-system and the exterior processes that affect it; and the outcomes, or performance criteria. Exterior processes include farming practices and environmental factors such as climate and geography, but also economic environment such as market prices for crops and agrochemicals. These are of different natures in that farming practices can be controlled, and therefore adapted to a set of requirements and conditions; on the other hand, market prices and climate are considered to be outside of the farmers' direct control, and must be adapted to. Within the system several processes and variables may interact with each other; the systemic approach involves taking into account all the relevant processes that affect the performance criteria, and are affected by human actions on the system.

CSD seeks to analyze the cropping system and find ways to optimize performance by modifying the farming practices (controllable external factors) to the conditions created by the environment (uncontrollable external factors). The sources of information used in CSD can originate from a wide variety of sources: scientists, agronomists, agricultural extensionists, farmers themselves, and/or other relevant stakeholders. Nevertheless, CSD is but one step in a larger process of improving performance of agriculture: achieving change in practices through prototyping, or testing of new farming practices.

### *1.1.2 METHODS FOR CSD*

There are two families commonly used approaches used by scientists for CSD: a) methods based on modeling of cropping systems, and b) methods based on mobilizing expert knowledge, notably farmers' knowledge. The knowledge of other experts can be mobilized as well (Loyce & Wery, 2006).

Models

Models of cropping systems summarize current scientific knowledge on a cropping system, its functions and the production processes. Their ability to take into account multiple factors, processes and outcomes has made them invaluable tools in CSD (Mendoza and Martins, 2006; Tixier *et al.*, 2006). Models allow researchers to test a large amount of changes to the cropping system under different environmental conditions with little to no cost. They simplify reality to a certain extent but focus on the main and important processes. This makes them suitable for working on systems with multi-criteria performance factors – proposals for cropping systems can be tested and evaluated based on these criteria in order to find the optimal solution (Dogliotti *et al.*, 2004). Models are also useful for managing the complex interactions and trade-offs present in certain cropping systems (Malézieux *et al.*, 2009).

The main kind of model referred to here is numerical process-based models (Hergoualc'h *et al.*, 2009; van Oijen *et al.*, 2010b). Other types of models exist, such as conceptual models (Lamanda *et al.*, 2011) and companion modeling (ComMod, 2005) and are discussed more lengthily in chapter 4.Process-based models depend on the precise identification and measure of the main factors affecting each process. As a result they depend on existing studies and data; their elaboration and construction is resources-heavy; but they remain a very powerful tool for effective CSD.

The downside of using numerical models in CSD lies in the poor rate of application to field- or farm-based experimentation.  This step is necessary to confirm the suitability of the proposed cropping systems; yet it is frequently overlooked due to lack of communication between researchers and farmers, or due to lack of interest of non-researchers in modeling approaches.

Participative approach

In this approach, the empirical knowledge of key experts and stakeholders is mobilized for the elaboration of cropping systems. This approach tends to yield cropping systems that respond to highly specific, local criteria; therefore, the suitability of the proposed systems tends to be much higher (Lançon *et al.*, 2007; Rapidel *et al.*, 2009). Since farmers are involved in the design process, the rate of adoption of new of modified practices is also higher (Vereijken, 1997). If the performance criteria also concern other groups of stakeholders, they may be involved in the design process as well. This approach is useful when models are not available, or the models do not take into account particularly innovative practices, or are not able to simulate the variables necessary for calculating the performance criteria.

These two approaches both present positive and negative aspects. Several attempts have been made to combine them in a multidisciplinary approach combining modeling and participation of farmers – most notably by Whitbread et al (2009).

### *1.1.3 INTEGRATING CSD INTO RESEARCH AND EXPERIMENTATION*

Designing cropping systems is not sufficient in itself in order to improve farming practices. The proposals of modified cropping systems need to be tested, adapted and eventually adopted in the field in order to generate significant changes. This approach, referred to as prototyping, has been theorized by several authors such as Sterk et al (2007) and Vereijken (1997). CSD is an integral part of the framework approach (see figure 1.1). The cropping systems produced at the design stages therefore have to be tested and comply with certain criteria in terms of effectiveness, practicability, performance, etc.

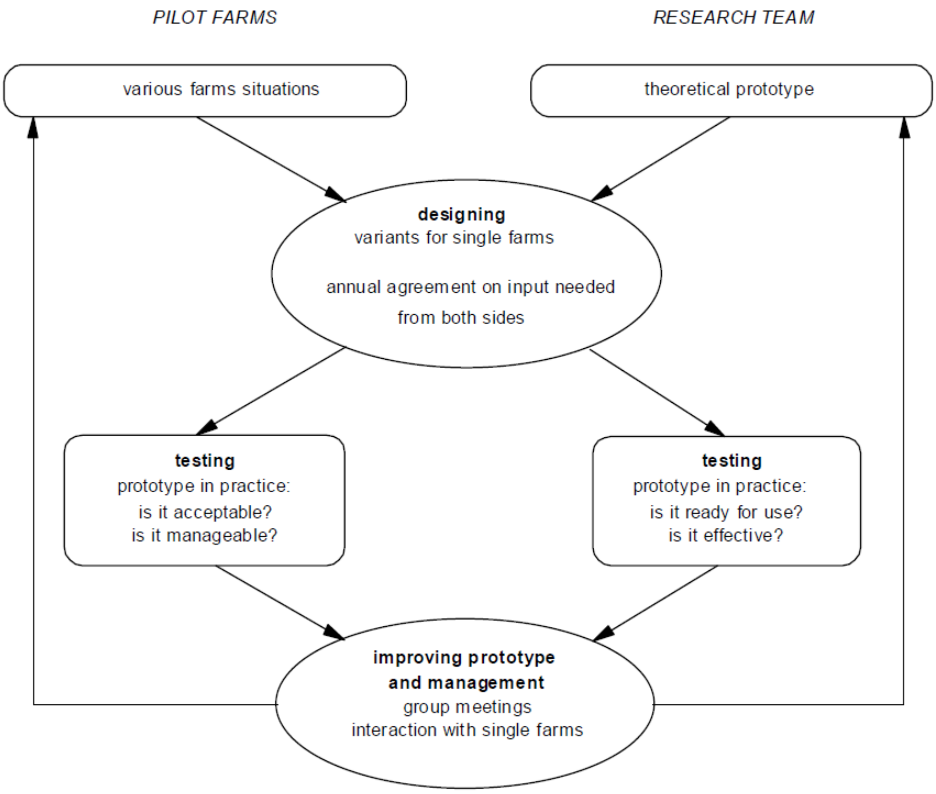


Figure 1.1 – framework for prototyping at the farm scale (from Vereijken, (1999))

Testing verifies the effects of changes in current practices. Positive results of in-field trials are strong arguments for new farming practices, and can ease the process of adoption by farmers. If negative, it raises questions on the suitability of the suggested practices. Defining a proper scale for application is also vital: the larger the study area, the wider the diversity of farmer constraints and environmental variability.

The testing phase of prototyping is mainly done via computer modeling, trials on experimental stations, or on-farm research or pilot farms. Each of these methods carried advantages and disadvantages:

- Models have relatively little cost if they are used as is, and offer a freedom of having a large amount of trials. But they remain a simplification of reality and the margin for error is sometimes quite large, or unknown.
- Trials on experimental stations offer good conditions for testing techniques on the field but their relevance may be limited to the specific conditions of the trial
- On-farm trials carry the advantage of directly involving farmers which creates realistic conditions but controlling all factors is hard; so is convincing enough farmers to participate

## 1.2 COFFEE-BASED AGROFORESTRY SYSTEMS

### *1.2.1 COFFEE BASIC PHYSIOLOGY AND FUNCTION*

*Coffea arabica* of the *Rubiacae* family, is a perennial flowering tree-type plant native to Eastern Africa whose seeds are used to produce coffee. It originates from Ethiopia where it is still grown today in shaded forests between 1400 and 1800m altitude. Although several other species of coffee exist, such as *C. canephora* (that produces Robusta coffee) and *C. liberica*, *C. arabica* remains the most widely cultivated species (Morton, 1977). Several smaller and higher-yielding varieties of *C. arabica* have been developed, such as Caturra or Bourbon, or Typica.

The optimal climate for Arabica coffee growth is situated at high altitudes (between 1200 to 2000m) in Subtropical or Warm Temperate climates, with ideal temperature between 20 and 27°C, 1500 to 2500mm of annual precipitation, and a soil pH from 4.5 – 7.0 (Wintgens, 2009). Coffee does not tolerate frost. A dry season of at least 2-3 months is required in order to trigger reproductive growth.

Once a year, the plant produces red or yellow epigynous cherries (often referred to as berries). The reproductive process begins after the last harvest, during a period of dry weather where the plant begins producing and maturing buds. Flowering of mature buds is triggered by rainfall. Arabica coffee flowers are mostly pollinated with the pollen of the same flower (*C. arabica* is autogamous). Cross pollination can also occur, triggered by wind, as well as insects (Klein *et al.*, 2003). Fertilized flowers then develop into cherries.

Coffee is generally planted in-field as a sapling, in rows of 1-2m width with 0.5-1m between each plant. Densities may vary, especially depending on slope, and can go from 5000 to 9000 plants per hectare in intensified systems. C. Arabica develops a straight trunk with paired branches emerging outwards. As branches grow they develop fruit nodes, where buds and/or leaves develop. Several buds may develop on a single fruit node (up to 25, but 2 or 3 on average) but only two leaves develop per fruit node – see plate 1.1. Branch growth continues from the exterior end outwards, with new fruit nodes progressively developing. Defoliated fruit nodes do not grow new leaves or buds (Cannell, 1975).

Plate 1.1 – coffee branch showing unopened flowers, buds, and leaves.

Each cherry contains two seeds, or coffee grains, which take 6-9 months to fully develop and ripen to their characteristic red color (yellow in certain varieties). Coffee is generally hand-picked in order to only harvest the ripened cherries and leave green cherries to further mature. In some large-scale plantations of flat land, such as in Brazil, mechanized harvesting of coffee is also possible. There are two main processes for transforming the coffee cherry:

- The dry method is the oldest way of preparing coffee: it consists of drying the entire coffee cherry, often in natural sunlight. Once dry (the process can take up to 4 weeks) the cherry is hulled and the grain is sorted and packed for sale.
- The wet method involves removal of the cherry pulp and washing of the grain in order to remove liquid remains of the pulp. The coffee is then dried in sunlight or using machinery, which causes the parchment to detach, making its removal possible. This method may involve substantial levels of water consumption as well as polluted effluents, however improved machinery and the use of water treatment processes can help improve the efficiency and reduce the environmental impact of the process. This is the method used for most of the *C. arabica* coffee produced.

Coffee cherries and grains may be sorted and graded before and after processing in order to generate different quality grades. The result of the whole process is known as “green bean” coffee, and it the most commonly form of coffee sold for export. Green bean coffee must then be roasted, typically at 240-275°C for 3-30 minutes – this process largely depends on the roaster and customer preference. Roasted coffee beans may be sold to the consumer whole, or ground.

### *1.2.2 PRUNING COFFEE PLANTS*

Coffee is a perennial plant which requires maintenance and special conditions in order to favor growth and production of cherries. In addition to common farming practices such as fertilization and weed control, coffee pruning has specific modalities for coffee cultivation. This section provides a brief overview of coffee pruning and its effect on plant physiology in order to facilitate understanding of discussion in later chapters.

As mentioned previously, coffee plants grow and produce fruit nodes. Defoliated fruit nodes (by leaf senescence or accidental defoliation during harvest and other interventions in the field) do not produce additional leaves or cherries, and the plant relies on continuous growth of its branches and stems in order to keep developing new fruit nodes every year. This can lead coffee plants to reach substantial girths and heights (sometimes in excess of 3m). Original *C. arabica* plants could easily reach this height, due to large spacing in between fruit nodes. Dwarf varieties such as Caturra have less space in between fruit nodes thus allow for smaller plants, easier to harvest.

Plate 1.2 – defoliated coffee plant due to die-back

Nevertheless, coffee plants suffer due to their inability to regenerate leaves and reproductive organs on old fruit nodes (Cannell, 1971; Chaves *et al.*, 2012). This can lead to large parts of the plant being non-productive and only the extremities having vegetative and reproductive growth. Eventually plant production ceases completely. Before this point, the plant is generally pruned at approximately 50 cm from the soil surface. This causes regrowth of several offshoots; between 1 and 4 offshoots are generally allowed to grow to full size. It takes on average 3 years for an offshoot to reach high yields again, although the offshoot does produce a small amount of fruit already in the first and second years after pruning. In order to stimulate the growth of each shoot and reach similar levels of production than the original plant, coffee farmers generally remove excess shoots at a young age to only leave one or two shoots per stem. Over time this may create coffee plants with a complex structure of several stems and shoots. However, a correctly pruned coffee plant may continue producing well beyond 25-30 years of age. Eventually shoot regrowth slows and stops, and the plant is considered dead. Furthermore, *C. arabica*, a shade tolerant species, has limited shedding of young cherries. When the blossoming is very intense, Coffee plants usually conserve a high number of cherries, higher than what the plants can feed with their photosynthesis (overbearing). Thus they have to consume their reserves. If the reserves are too depleted, then the leaves shed, and the plant loses its capacity to grow again the next year. This is known as die-back (see plate 1.2 below). At the plot scale, pruning is either done selectively (by removing plants with too high a ratio unproductive nodes to productive nodes, or presenting signs of die-back) or, in larger plantations, entire rows of plants are cut at regular intervals of 3 to 6 years.

### *1.2.3 COFFEE FARMING IN CENTRAL COSTA RICA*

Coffee cultivation has strongly influenced Costa Rican economy, society and agricultural landscape since it was brought to the country in the 1800s (Samper, 1999). Today, the country's annual production reached 90 thousand tons annually, of which 85% is sold for exportation. This creates an annual income of over 250 million USD (ICAFE, 2011).

Over the years coffee cultivation has seen significant changes. While coffee was traditionally grown under dense shade tree canopy of various species, many farmers have converted to high-yielding systems with intensive use of agrochemicals (Rice, 1999). Drops in the price for coffee on the global market has led Costa Rica to favor the development of high-quality coffee sold at a premium price as well an social and environmental certification schemes (LeCoq *et al.*, 2011).

The Tarrazù valley region (see figure 1.2) is of particular importance in national coffee production.


Figure 1.2 – map of Costa Rica with central valley region in the red rectangle

Plate 1.3 – landscape covered in coffee plantations in the Llano Bonito valley, central Costa Rica

Due to optimal conditions for coffee growth, this region (along with the neighboring Dota valley) has the highest yield rates in the country and coffee is intensively grown (ICAFE, 2007). Plate 1.3 shows an example of the mountainous landscape of the region, where coffee is by far the major land use.

The size of coffee farms varies enormously, from small, family-sized holdings to large properties of many dozen hectares. In Costa Rica, some large farms can afford their own processing plant and direct sale to buyers, but smaller farmers rely on local cooperatives and private companies who have their own processing plants installed. At harvest time, ripe cherries are deposited at receiving stations scattered around the area where the coffee cherries are weighed and farmers are paid per volume. Prices can vary significantly from year to year and depend on the global market as well as the quality grade of the coffee.

<u>Erosion in coffee plantations</u>

Coffee can be planted on extremely steep slopes, although this prevents the use of mechanical apparatus. As a perennial crop it provides a year-long cover which helps to maintain the soil structure and prevent plot-scale erosion (Lin and Richards, 2007). Nevertheless, with an annual rainfall of 2500-3000mm per year, important amounts of sediment are still loaded by rivers every year and especially during the wet season, which lasts from April to November. This creates problems for the numerous hydroelectric dams in Costa Rica, which generate over 85% of the country's electricity. The dams are owned by the National Electricity Institute (ICE) which has recognized that soil conservation is a high priority in watersheds upstream of hydroelectric dams (Melendez Marin, 2010).

### *1.2.4 THE ROLE OF SHADE TREES IN COFFEE IN COSTA RICA*

Agroforestry functions on the basis that combining trees and crops brings in more resources than if the trees and crops were grown separately, or that the crop was grown on its own (central agroforestry hypothesis by (Cannell *et al.*, 1996)). Trees can provide a large variety of ecosystem services that may be valued by different stakeholders. Carbon sequestration (Albrecht and Kandji, 2003), refuge for biodiversity (Bhagwat *et al.*, 2008), economic returns from the sale of timber (Beer *et al.*, 1998) and nitrogen fixation by leguminous species (Nygren and Ramírez, 1995) are just a few common examples of benefits generated by trees in agroforestry systems.

Shade trees are particularly important for coffee growth. Coffee was originally grown in shaded forests; although new varieties tolerate lower shade levels, trees still play an important role in microclimate regulation and nutrient cycling in coffee plantations. A more detailed overview of the effect of shade trees on coffee can be found in chapter 2.

Up to now shade trees have been mentioned without referring to particular species. This is because the species used in coffee agroforestry systems across the world vary immensely. Nevertheless, in Costa Rica, a few tree species tend to dominate – notably *Erythrina poeppigina*. Erythrinas are particularly appropriate for coffee plantations in Costa Rica – they are easy to prune and regrowth is fast, allowing for an easily controllable shade cover (Russo and Budowski, 1986). This feature is particularly appreciated by farmers who sometimes reduce the shade cover to 0% during times where higher levels of sunlight are needed. Erythrina trees also bring benefits common to other shade tree species, such as nitrogen-rich leaf litter (Payán *et al.*, 2009), protection against excess evapotranspiration and water stress (Lin, 2010), improved coffee quality (Muschler, 2001), and biological nitrogen fixation (Nygren and Ramírez, 1995). Erythrina shade can also have adverse effects in certain conditions, such as creating more favorable conditions for pests and diseases (Avelino *et al.*, 2005).

Generally Erythrina trees are pruned once or twice a year, before the coffee flowers in March-April and in the last stages of coffee cherry maturation in September. The pruning intensity varies from farmer to farmer, although as shown in plate 4, complete removal of almost all branches is frequent, leaving thick tree trunks with three or four young branches.

Plate 1.4 – *Coffea arabica* (Caturra variety) grown under regularly pruned *Erythrina peoppigiana*

## 1.3 OBJECTIVES AND THESIS STRUCTURE

### *1.3.1 RESEARCH HYPOTHESES*

We have seen that several possible approaches to CSD exist. Each one carries advantages and benefits. However, what would the possibilities be of combining modeling and participatory approaches in order to improve CSD? Before further defining this question, we must make several assumption about the methodology used.

First of all, we hypothesize that, for a given agronomic situation, there would exist an appropriate model (or several models) that could contribute to the CSD process of a particular cropping system. The model(s) would summarize current scientific knowledge and data, often scattered, for performing simulations of variable input factors, such as environmental conditions or farming practices.

Secondly, how would the two methods be combined together to respond to an agronomic problem? The model would need to be able to be integrated into the participative research. There would be a way for the farmers and other relevant stakeholders to interact with the model, directly or indirectly. Furthermore, the model would allow us to work with variables that are not easily grasped or observable by the farmers (such as erosion). These new variables and information would stimulate farmers' thoughts on the diagnostic and design of their own crops and envision changes to their farming practices, sometimes outside of the range they initially imagined.

Our choice of the case study was also guided by certain assumptions. We hypothesized that the combination of family-based agriculture with intensive farming practices made likely that trade-offs situations would already have been reached, at least in some coffee plots. Coffee production in central Costa Rica is well developed, supports many livelihoods and is likely to continue in the long-term. In this context, we decided that attempting to propose a change in farming practices to decrease erosion control would be a significant enough challenge for the model so that this method would truly be tested.

Finally, how do we evaluate the success of our method for generating cropping systems that correspond to our objectives? The format of the farm-model interactions would generate variables that can be evaluated based on their scientific soundness and the practicability of the suggested systems would need to be evaluated.

### *1.3.2 THESIS OBJECTIVES*

The aim of this thesis is therefore to investigate what benefits are gained and which obstacles are encountered when combining modeling with participatory work in CSD. Specifically, we aim to test this question in the particular setting of coffee-based agroforestry system in central Costa Rica.

In this context, this thesis sets to answer three major research questions:

1. Within a defined production area, how does the diversity of farming practices, constraints and trade-offs between coffee production and erosion at the plot scale affect the suitability of erosion control practices?
2. What are the factors affecting the relationship between shade trees, coffee production, and erosion control, and can a model help optimize this relationship for increased provision of ecosystem services?
3. How can we bring Costa Rican coffee farmers to interact with the model, and what benefits can this interaction generate?

### *1.3.3 PROPOSED METHODOLOGY*

In order to answer the proposed research questions, we propose a methodology divided in four main stages. In this thesis, each stage corresponds to a chapter.

- Combining a conceptual model and typology of farming practices for the appraisal of the diversity of farming practices, constraints and trade-offs at the plot scale between coffee production and erosion in a defined production area (chapter 1)
- Using field data to evaluate the impact of shade trees on coffee production and erosion within the study area (chapter 2)
- Selecting and calibrating a numerical model that respond to the needs and objectives of our study (chapter 3)
- Evaluating whether combining the numerical model and participation of farmers can yield proposals for on-farm experimentation of cropping systems with improved erosion control, that farmers find acceptable (chapter 4)

This method solicits various sources of information at different stages, which are illustrated in the diagram below (figure 2 below).

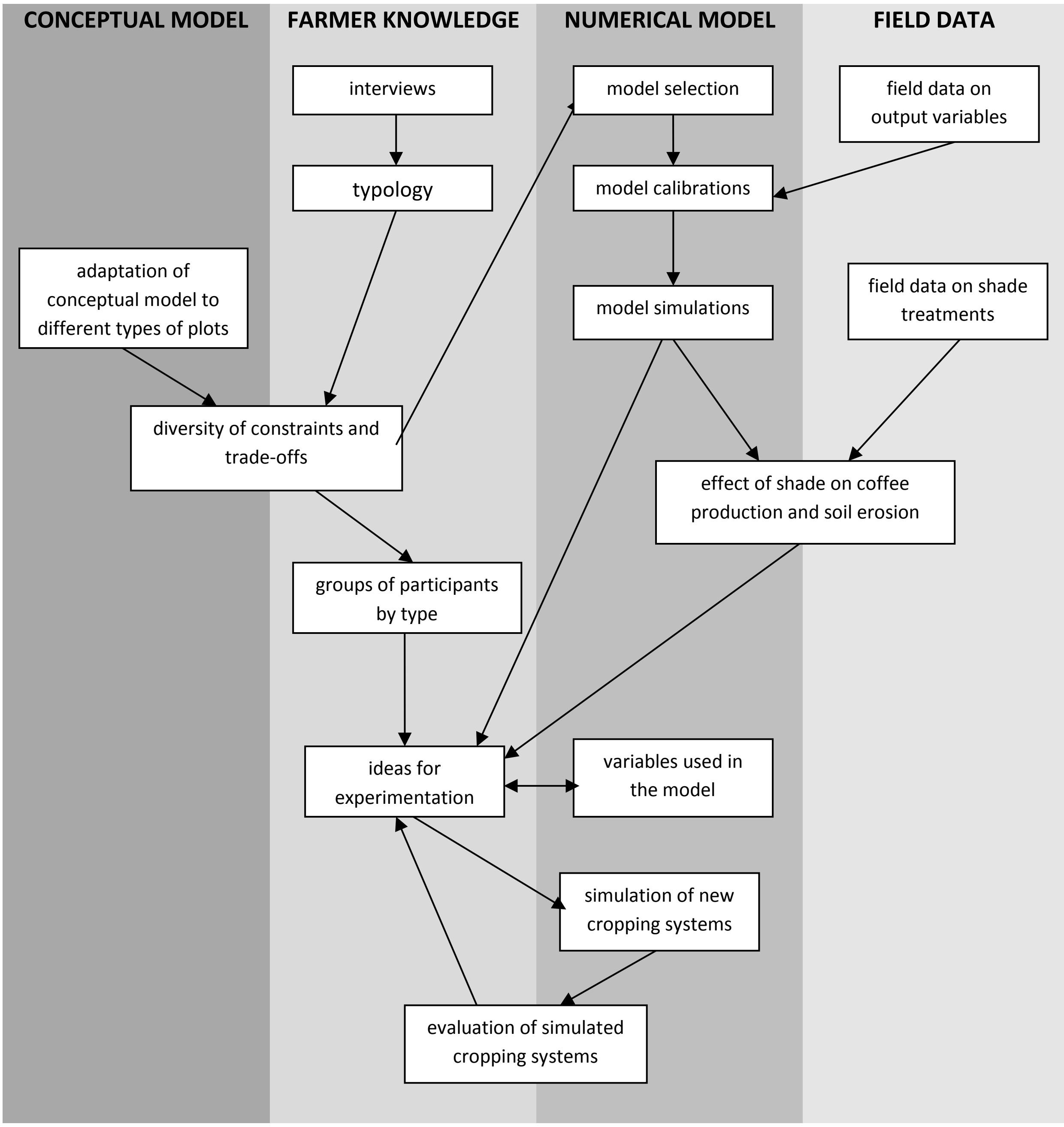


Figure 1.3– schematic diagram representing the role of different information sources during the thesis project

Generally, the first three steps can be seen as a preparation to the final stage, in chapter 4, which describes the actual testing of the combination of modeling and participatory approaches. Nevertheless, these stages are essential to the process as they ensure that the interaction between farmers and model yields the best possible results – in other words, that the model is given a chance to perform its intended function, making the evaluation fairer.

First of all, the initial phase of using the typology in combination with a conceptual model is a first test in crossing farmer and scientific knowledge, in the sense that we gain information on the constraints to implementing certain erosion control practices. This creates a significant gain in the accuracy and appropriateness of the simulations later proposed since suggesting unfavorable practices is avoided or more carefully approached. Secondly, this allows us to orient our model selection for the following stages, since this first stage would let us know what critical processes and factors we need to take into account.

Considering numerical models tend to be generic, having field data as a reference was vital. Numerical models generally require calibration before use in order to ensure they function as expected and simulate the cropping system with a minimum of accuracy. Field data were therefore needed for this purpose. Models can also be validated against field data (not the same set used for calibration) in order to evaluate their accuracy. Finally, field data can be used as a tool for discussion with farmers to broach the topic of quantitative relationships between processes, as a way of introducing the numerical model.

All of these steps lead to the stage where farmers and numerical model interact via discussion on design of cropping systems for experimentation. As mentioned previously, this phase integrates itself in the prototyping framework. Although this thesis stops at the generation of proposals and the evaluation of their suitability by the farmers, the subsequent link to evaluating on-farm implementation of these cropping systems is evident.

# CHAPTER 2

# COMBINING A TYPOLOGY AND A CONCEPTUAL MODEL OF CROPPING SYSTEM TO EXPLORE THE DIVERSITY OF RELATIONSHIPS BETWEEN ECOSYSTEM SERVICES

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# COMBINING A TYPOLOGY AND A CONCEPTUAL MODEL OF CROPPING SYSTEM TO EXPLORE THE DIVERSITY OF RELATIONSHIPS BETWEEN ECOSYSTEM SERVICES

## The case of erosion control in coffee-based agroforestry systems in Costa Rica.

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**ABSTRACT**

With increasing pressure on farmers systems to increase the performance of their cropping systems, there is a growing need to design cropping systems that respond concurrently to environmental, agronomic and socioeconomic constraints. However, the trade-offs between ecosystem services, including provisioning services, can vary considerably from plot to plot. Combining a typology of agricultural practices with a conceptual model adapted to plot context can provide an instrument to support the design of cropping systems that take into account the diversity of environmental and socioeconomic conditions and trade-offs within a study site. This method was tested to design coffee-based agroforestry systems mitigating soil erosion in central Costa Rica, a case study with a high-value crop in a complex relationship to its biophysical environment. Quantitative data on agricultural practices and costs were collected over two years on a sample of plots in an 18km$^2$ watershed upstream of a hydroelectric dam. A typology of plots was built based on agricultural management practices; the resulting groups were further characterized by socioeconomic and environmental variables. In parallel to this, a generic plot-scale conceptual model representing the effect of agricultural practices and environmental factors was designed, with erosion reduction, coffee production and gross margin as the outputs. The critical variables from each group of plots were used to adapt the model to the groups from the typology. The four groups found were 1) low-intensity management; 2) intensive management; 3) shaded agroecosystem, and 4) intensive agrochemical management. The conceptual model helped analyze the key processes and trade-offs for each group and helped make recommendations of adapted erosion control practices. The model showed that less time-consuming erosion control actions not impacting coffee production might be more suitable for group 1, such as drainage canals, terraces, and vegetative barriers. In contrast, plots in group 3 had more sunlight as well as investment of money and labor, opening the possibility of using shade trees or manual weed control (as opposed to herbicide use)

to control erosion. This method finds its application in the plot-scale design and prototyping of agricultural systems that better respond to specific constraints, and can provide more relevant basis for discussion with farmers in participative methods. It also presents the advantage of requiring little data acquisition, although it can be further developed through integrating numerical relationships for quantitative modeling.

## 2.1 INTRODUCTION

Increased demand on agricultural lands for both productivity and decreasing environmental impact puts pressure on farmers and decision makers to improve the performance of these systems. This has created renewed need for research in ecological intensification, or the increased function of ecosystem services (ES) in cropping system design (Doré *et al.*, 2011). Provisioning services (production of food, fiber, energy, *etc*.) and other types of services, i.e. regulating, supporting or cultural, are often in competition with each other (Brussaard *et al.*, 2010). A trade-off situation occurs when two ES reach a level where an increase in one implies a decrease in the other. The identification of trade-offs or synergies between ES in agricultural systems is a high priority for current research (Power, 2010).

In an agricultural system with scope for technical improvement, based on ecological and agronomic knowledge, it may be possible that provisioning and other services can be enhanced simultaneously in a win-win situation (McShane *et al.*, 2011). But in highly productive cropping systems, such as high-value crops for export, it is more likely that trade-off situations occur instead. Additionally, small losses in productivity may represent significant income loss.

When designing sustainable cropping systems, the impact of providing more ES, and whether a trade-off situation has been or will be reached, has to be carefully evaluated. This includes the potential value of the ES to the farmer, which may support production (e.g. soil fertility) or control processes which affect production negatively (e.g. pest control). In other cases, provision of ES may carry a financial compensation offered by other interested stakeholders (Kosoy *et al.*, 2007).

Agroforestry systems (AFS) consist of mixed tree and crop or livestock systems (Torquebiau, 2000). Such systems present a complex spatial and temporal structure. They are thought to offer increased opportunities for combining provisioning services with other types of services (regulating, supporting, or even cultural) (Tscharntke *et al.*, 2011). The potential environmental benefits of having trees in the system include provision of habitat and refuges for biodiversity (Bhagwat *et al.*, 2008), carbon sequestration (Albrecht and Kandji, 2003), microclimate regulation, and nitrogen fixation for leguminous species (Youkhana and Idol, 2009), among others. In addition, many livelihoods in developing and/or tropical countries depend on AFS for subsistence, economic income and other services, for example through sale of wood for timber (Malézieux *et al.*, 2009) or increased food security. AFS therefore present potential for production of additional ES (Izac and Sanchez, 2001).

In cropping system design, the gains and losses of AFS must be carefully weighed. For example, coffee is a perennial crop that is frequently grown under shade trees. It has been recognized that although shade trees bring many benefits to coffee plantations (Beer *et al.*, 1998), especially in sub-optimal cultivation zones (Muschler, 2001), these benefits may be outweighed by negative aspects, such as competition for light when coffee growing conditions are already optimal (DaMatta, 2004). Pests and diseases will also react differently to varying shade levels according to local geography (Avelino *et al.*, 2005). Nevertheless, the additional canopy cover, leaf litter and subsequent soil cover, and root structure brought by trees can significantly reduce the runoff and erosion potential at the plot scale (Sentis, 1997).

Within one production system, the relationships between ES present at the plot scale can vary considerably. Spatial heterogeneity (Antle and Stoorvogel, 2006), farmer constraints (Bernet *et al.*, 2001) or socioeconomic variables (Edwards-Jones, 2006) can all influence the state, performance and management of the cropping systems. This paradigm is summarized by Blazy *et al.* (2009) at the farm scale and identified as a key aspect of successful design of cropping systems and their management. It is also important at the field scale, where the relationships between ES may vary in their nature and intensity (Rapidel *et al.*, 2006). Methodologies for cropping system design must strike the right balance between taking into account local determinisms in order to increase chances of being used by farmers (Vanclay, 2004) and being sufficiently generic in order to be applied to other production areas and situations of a similar nature. This is important to ensure farmers' willingness to adopt or take interest in the changes and innovations proposed (Blazy *et al.*, 2011). This step usually precedes a prototyping exercise and implementation of field trials; completing it in a timely and efficient manner helps improve the reactivity and appropriateness of the solutions proposed.

Information on agri-environmental conditions, constraints and management practices can be gathered through farmers interviews (Merot *et al.*, 2008) or it may be deduced from quantitative data such as amount of product applied or hours spent on different practices. A typology of practices is then typically used to identify groups with common practices or characteristics – the range of groups representing the diversity of management practices and corresponding environmental situations. Blazy (2009) used this method to study the diversity of farming contexts and performance for prototyping new cropping systems.

Conceptual models can be a useful tool for representing complex cropping systems and the impacts of human activities. They can be used in the design of cropping systems, since conceptual models allow to explore the effects of changes to the systems and the impact on provision of ES (Le Gal *et al.*, 2010). This is particularly useful when the system has a certain level of complexity e.g. multiple species present or spatial heterogeneity, making a visual and functional representation necessary in order to thoroughly evaluate the impact of changes in crop management. Models have also been used as a support for discussion with farmers, for example through participative modeling design (Naivinit *et al.*, 2010) or interaction with an existing model (Carberry *et al.*, 2002). Conceptual models can also integrate local knowledge in order to take local specificities into account and provide a visual summary of theoretical and practical knowledge of a system (Lamanda *et al.*, 2011).

To address the complexities that encompass the trade-off between ES in an AFS, the information gathered from a typology of local cropping practices can be integrated into a conceptual model of the cropping system. The model can be built to be as complex and thorough as needed, and then allow us the freedom to adapt or simplify it in order to meet the needs of the farmer or group of farmers concerned. Therefore, the focus can be put on the most sensitive relationships and key constraints for different groups determined in the typology.

This paper aims to explore scenarios for the management of ES in AFS while considering the diversity of environmental and socioeconomic constraints within a production area. We hypothesize that the development and adaptation of a conceptual model showing the impact of management on production and other ES could be useful for evaluating a diversity of agri-environmental scenarios in a complex and highly productive system such as coffee-based AFS in central Costa Rica. Specifically, we aim to combine the conceptual model and typology approaches for a) characterizing the diversity of relationships between ES at the field scale across a production area and b) facilitating the prototyping process by more rapidly identifying constraints and opportunities for improvement. This methodology is applied in coffee-based AFS. We chose the Llano Bonito watershed, located in the heart of Costa Rica's coffee producing region in the Central Mountains, as our study site.

## 2.2 METHODOLOGY

### *2.2.1 STUDY AREA*

The study area chosen was Llano Bonito, a narrow 18 km² valley in the central mountains of Costa Rica in the Tarrazú/Los Santos region. The climate follows a well-defined wet/dry season pattern with 1491mm average annual rainfall. Altitude ranges between 1400 and 1900 m. The main crop cultivated is coffee (*Coffea arabica*) of the dwarf "Caturra" variety, grown under shade trees, mostly Erythrinas (*Erythrina poeppegiana mainly*) or varieties from the banana family (*Musa* spp) (banana and plantain trees). The region is further characterized by steep slopes, up to 80% in coffee plantations, and ultisols with high clay content.

High quality coffee is produced in relatively homogenous, highly productive AFS, yet with environmental problems, especially in regards to soil erosion and excessive fertilizer use. The steep slopes in which the coffee plantations are installed make them especially prone to laminar and mass erosion, questioning the long term sustainability of coffee production. These threats are further compounded by the recent building of a hydroelectric dam downstream, which entered into operation in 2011. The managers of this dam are promoting a better management of the watershed, to help delaying dam filling with eroded sediments (Meléndez Marín, 2010). Nevertheless, with good coffee prices, particularly in this region of good and well-known coffee quality, any erosion-controlling practice that encompasses reduction in production would be carefully considered by farmers.

The Llano Bonito watershed has been defined as a priority soil conservation and erosion reduction area by the ICE, Costa Rica's national electric and utility company who owns and manages the numerous hydroelectric dams in the country (Meléndez Marín, 2010).

### *2.2.2 CHARACTERIZATION OF THE DIVERSITY*

Data collection

Around 600 farmers live in the watershed, practically all of whom cultivate coffee in farms from 0.25 to 10 hectares in size. Nevertheless, farmer reliance on coffee sale for income varies considerably, as does the intensity of production (from four to nine tons of coffee/ha/yr).

Data was collected over a sample of coffee plots in order to help build the conceptual model and a typology of agricultural practices at the plot scale. Thirty-two of the estimated 600 coffee farmers in the watershed were interviewed. Location and size of farms was obtained from local cooperatives and ICAFE, the Costa Rican national coffee institute. The sample was spread out in order to obtain a balanced sample of farms located on the east and the west side of the watershed, and large and small farms, which were the factors suggested by local technicians that most explain the diversity of management practices as well as being reliably recorded. The database of farms provided by the local cooperative (Ortiz, 2010, personal communication) were first divided into three groups of equal numbers by size – small, medium and large sized farms (0-0.6 ha, 0.6-1.1 ha, and 1.1-10 ha respectively). Each size group was then separated according to their location on the east or west side of the valley. Within each of the resulting six groups, five to seven farmers were randomly chosen in order to constitute a pool of 32 interviewees.

A complete inventory of practices for coffee management was built on the basis of interviews with the coffee farmers. Farmers were asked to describe the management of a randomly selected coffee plot on their farm. The survey was performed twice, once in 2010 for 2008-2009 and a second time in 2011 for 2009-2010, each time covering an entire coffee growing season from the end of one harvest to the next one. Notable differences between the two years were an increased rainfall for 2009-2010 as well as a 38% increase in the price paid by the main local cooperative for coffee.

Recorded variables from the interview included: tool or substance used and in what quantity, chemical composition if relevant, time of year, hours worked and if the labor was paid or free (individual actions or help from family). Costs of products and of labor were recorded as constants per liter/gram of product and per hour of work. Cost of harvest was counted as a cost per unit of production since coffee pickers are paid per volume collected. Coffee and tree density, tree species present, area, and slope, were measured during a visit of the plot. The plot yield was also recorded from this interview. The active ingredients, prices of inputs and coffee price were obtained from the cooperative.

Table 2.1 – calculation of anti-erosion practices score (ERSN)

| **Practice** | **Possible score** |
|---|---|
| Pruning residues | 0 = taken for firewood (by landowner or workers)<br>0.33 = left on site without cutting twigs<br>0.66 = twigs cut and left on site<br>1 = twigs cut and left against the stem of other plants |
| Terracing | 0 = did not make or maintain terraces<br>1 = manually created terraces |
| Vegetative barriers | 0 = did not have any vegetative barriers<br>1 = has planted vegetative barriers some or all edges of plot |
| Canals | 0 = did not have any drainage canals to manage excess runoff<br>1 = has dug canals in order to drain excess runoff |

Due to lack of time and resources, erosion was not directly measured in the plots. Instead, several variables relating to soil conservation were built. Farmers were specifically asked to list ways in which they managed erosion and/or protected their soil and their perception of erosion as a problem or not (table 2.1). Additionally, Ataroff & Monstaerio (1997) show that there is a negative relationship between erosion and total Leaf Area Index of shade trees and coffee plants in a plot. Therefore, coffee and especially tree density were taken as proxies for soil conservation at the plot scale, in order to have a quantitative variable with which to examine trade-offs with coffee production.

Information relating to socioeconomic background was also asked for, such as age, number of children, number of years of ownership of the plots. The cost of coffee harvesting was calculated as 20% of the sale price of coffee, based on average sale prices and cost of paying coffee pickers in the study area from 2008-2010. In order to give an indicator of work productivity or interest in investing more work in the plot, the gross margin was divided by the total number of hours worked.

Typology

The variables collected during the interviews were used in a typology based on plot-scale management practices, in order to determine groups of plots with similar management characteristics which could then be associated with additional environmental and socioeconomic criteria.

In order to have a scaled comparison of practices with relatively more or less importance in relation with the expected ES, most of the management practices were expressed as one of the following units:

- the cost of chemical products (fertilizers and pesticides) used on the plot, in USD per hectare per year,
- the number of work hours required for each operation, in hours per hectare per year.

The cost of fungicides was considered separately as an indicator of fungus attack, especially for *Mycena citricolor*, a common fungus in Costa Rica (Avelino *et al.*, 2005).

In addition to these variables, tree density, coffee plant density, and a score reflecting the number of soil conservation practices in place were included as separate management variables. The list of the variables used for the typology is indicated in table 2a.

Table 2.2a – list of management variables used as criteria for PCA analysis

| **Variable** | **Description** | **Unit** |
|---|---|---|
| FERT | Amount spent on fertilizer (N, P and K) | USD/ha/yr |
| FOLI | Amount spent on foliar fertilizer | USD/ha/yr |
| FUNG | Amount spent on fungicide (active ingredient: tebuconazol) | USD/ha/yr |
| HERB | Amount spent on herbicide (glyphosate-based) | USD/ha/yr |
| NFER | Hours spent on applying urea-based fertiliser | hrs/ha/yr |
| NFOL | Hours spent on applying foliar fertilisation | hrs/ha/yr |
| NFUN | Hours spent on applying fungicide | hrs/ha/yr |
| NHER | Hours spent on applying herbicide | hrs/ha/yr |
| NTRE | Hours spent pruning trees | hrs/ha/yr |
| NCUT | Hours spent manually cutting weeds | hrs/ha/yr |
| NPRU | Hours spent pruning coffee | hrs/ha/yr |
| TREE | Density of trees (all species mixed) | N° of trees/ha |
| COFF | Density of coffee plants | N° of plants/ha |
| ERSN | Number of practices to actively control erosion | Score from 0 to 3 |

After the analysis, a set of additional descriptive variables (Table 2b) were used to further characterize the groups found in the typology. Total size of the coffee farm and time of sunrise on the plot (linked to the total amount of sunshine received) were indicated as potential predictors of differences in groups (Ortiz, 2011, personal communication). Slope is a frequently cited factor linked to erosion; and yield and gross margin were used as performance variables.

Table 2.2b – list of additional variables to describe the plots

| Variable | Description | Unit |
|---|---|---|
| AREA | Total size of the coffee farm (sum of the area of all plots measured by GPS) | Hectares (ha) |
| TIME | Time of sunrise on the plot | hh:mm |
| YIEL | Total amount of dry coffee sold from the plot | Kg of coffee/ha/yr |
| SLOP | Slope | % |
| GMAR | Gross margin (income from yield – cost of paid labour and agrochemicals) | USD/ha/yr |
| INCO | Percentage of income that comes from sale of coffee | % |
| WORK | Work productivity (Gross margin / Total number of hours of work, excluding harvest) | USD/hrs |

The variables from Table 2.a were analyzed in a Principal Components Analysis (PCA) in SPSS 17.0 in order to determine the main axes by which the practices on plots could be explained. A descendant hierarchical cluster analysis was then performed on the first axes found in the PCA. The cutoff point was chosen at 50% of explained variability in order to give weight to the variables that most explained the differences in between groups, which are more represented on the first few axes (Blazy *et al.*, 2009). Applying the cluster analysis on the coordinates of each individual on the PCA axes instead of on the raw data has the advantage to not give excess weight to outliers. Using a dendrogram chart, three to six groups, with minimum 4 plots per group, were made based on a cut-off made at the largest branch distance. These groups would represent plots with common management variables determined by the axes from the PCA. In order to characterize each group, the means and standard errors were calculated for each variable in Table 2a and 2b and Tukey's range test was used to test for significant difference between all the means.

### *2.2.3 CONCEPTUAL MODELING*

Construction of conceptual model

The objective of constructing a conceptual model was to represent, at the plot scale, the diversity of constraints and variability of the trade-offs present in the production area. The construction of the model was based on the methodology outlined by Lamanda et al (2011). We used the first two steps in order to construct a **general model** for coffee-based AFS: 1) structural analysis, the definition of model scope and elements, and 2) functional analysis of the processes in between these elements. The model was constructed on the scale of a coffee plot for one growth year.

Model components

The model was divided in three large categories; a) inputs: the physical factors and management practices affecting the system; b) the biophysical coffee-based AFS itself; and c) the performance of the system represented by selected outputs (Lamanda *et al.*, 2011).

For the **inputs** to the model, physical factors included climatic, geographical, and environmental factors, as well as socioeconomic factors. Management practices included agricultural practices in the coffee plantation, as well as any technique mentioned by the farmer to control erosion and protect soils, in and around the coffee plot. These inputs were only included if they either varied significantly across the study area, or if their importance was likely to vary from plot to plot. Research was first based on literature and interviews with technicians in order to find the range of possible inputs. This range was then decreased to keep only the inputs relevant to the study area, based on the content of the interviews.

The **biophysical system** included the coffee AFS and its biophysical elements that were affected by the inputs and/or that affected the ouputs, as well as intermediary elements necessary to distinguish or add more detail to complex processes.

The **outputs** chosen for this model were based on the priorities determined by stakeholders: in this case, yield and gross margin, considered key variables by the farmers, and reduction in sediment loss, the ES expected by the dam managers.

Functional analysis

Links needed to be built between the elements of the model in order to represent specific processes. These processes would describe the effect of the management practices and external factors on the biophysical system; and the factors in the biophysical system which affected the system performance.

Each link or process was documented as a hypothesis; the information to support these hypotheses was obtained from different categories of sources:

a) scientific literature review based on articles relating to coffee-based agroforestry systems;
b) discussions with technicians;
c) discussions with farmers.

Information from literature and technicians helped to build hypotheses on generic relationships in coffee-based AFS, while information gained during the farmers' interviews in the production area allowed for local and specific aspects of the system to be integrated into the model. Technicians were chosen to better inform the processes affecting the performance of the system; for example, the coffee technician from the local coffee cooperative, and the hydrologist from the team studying environmental impacts on the hydroelectric dam downstream. Information was gathered by asking for a description of the cropping system and which elements and processes affecting coffee production and erosion

When choosing which processes to include in the model, it was decided that the model itself only needed to be complex enough to distinguish the effects of the active environment on the system, and the different factors affecting the passive environment. For the sake of parsimony, elements were discarded if it they could not be linked to a documented process.

Characterizing the groups

Once a general model for the study area was made, the model was adapted to reflect the critical processes for each group of plots. This was done via a selective removal and greying out of non-critical elements or processes. The process began with the management variables (model input). Arrows originating from the management variables were colored either in **RED** to signify a significantly higher/stronger value for that element compared to the other groups, or in **BLUE** to indicate significantly lower/weaker values. The values were taken from the outcome of the typology and Tukey's range test, which compared the means of each management variable between each group. An absence of significant difference with the other groups resulted in a greying out of that management practice and removal of the arrows which stemmed from it.

An agronomic interpretation was then used to justify maintaining red or blue arrows (or removing them) for the subsequent elements which were affected. Any element which ended up with no arrows connected to it was greyed out.

The end result was a simplified version of the initial general model with only the key elements and processes for each group. Each adapted version of the model was then used to study the relationship between erosion and coffee production and/or gross margin, using the highlighted elements and processes of the model as indicators of key or critical aspects for that group. The analysis centered around which key or critical processes affect both erosion and yield in order to identify any interactions. The nature of these interactions was then analyzed .

## 2.3 RESULTS

### *2.3.1 INTERVIEWS*

The average values for hours of labor for each practice and the average spending on each type of input were compared in figures 1a and 1b. The cost of picking coffee at harvest time was the most important expense, although the cost calculated did include the work of the farmer and unpaid help from family/friends. In terms of cost of products, figure 1a shows that fertiliser represents the highest expenditure in terms of chemical inputs at a mean of 995 USD/ha/yr for all plots.

Table 2.3 – Mean values for management and other variables, years 2008-2009 and 2009-2010. (Tukey's range test, significance level 10%) – values followed by the same small letters (a,b,c) in a line indicate no significant difference within them

| Variable | General mean | Unit | ANOVA results | | | Mean group 1 "low intensity" | Mean group 2 "labor intensive" | Mean group 3 "shaded system" | Mean group 4 "agrochemical intensive" |
|---|---|---|---|---|---|---|---|---|---|
| | | | Sum of squares | F | P/Sig. | | | | |
| **N** | 8 | - | - | - | - | 8 | 9 | 9 | 6 |
| **FERT** | 994 | USD/ha/yr | 4 887 424 | 23.2 | **0.00** | 518 c | 1 395 a | 909 b | 1 157 a,b |
| **FOLI** | 5 | USD/ha/yr | 2 633 | 31.8 | **0.00** | 1 b | 4 b | 1 b | 22 a |
| **FUNG** | 40 | USD/ha/yr | 50 496 | 4.5 | **0.01** | 51 a,b | 28 b | 16 b | 79 a |
| **HERB** | 15 | USD/ha/yr | 6 536 | 10.2 | **0.00** | 6 b | 5 b | 24 a | 28 a |
| **Total USD/ha/yr** | 1054 | USD/ha/yr | 4 938 696 | 26.4 | **0.00** | 576 c | 1432 a | 950 b | 1286 a,b |
| **NFER** | 87 | Hours/ha/yr | 67 801 | 14.5 | **0.00** | 60 b | 122 a | 81 b | 85 b |
| **NFOL** | 3 | Hours/ha/yr | 986 | 17.4 | **0.00** | 2 b | 3 b | 0 b | 13 a |
| **NFUN** | 11 | Hours/ha/yr | 9 349 | 4.9 | **0.01** | 22 a,b | 7 b | 3 b | 28 a |
| **NHER** | 28 | Hours/ha/yr | 11 598 | 5.4 | **0.01** | 25 a,b | 13 b | 36 a | 44 a |
| **NTRE** | 20 | Hours/ha/yr | 2 803 | 0.1 | 0.96 | 21 a | 18 a | 19 a | 20 a |
| **NCUT** | 150 | Hours/ha/yr | 332 547 | 1.1 | 0.35 | 131 a | 203 a | 120 a | 144 a |
| **NPRU** | 84 | Hours/ha/yr | 54 899 | 3.7 | **0.02** | 71 a,b | 120 a | 68 b | 77 a,b |
| **Total hours/ha/yr** | 383 | Hours/ha/yr | 622 270 | 8.0 | **0.01** | 332 b | 486 a | 327 b | 411 a |
| **TREE** | 361 | N° of trees/ha | 1 620 206 | 3.4 | **0.03** | 288 a,b | 332 a,b | 539 a | 235 b |
| **COFF** | 6 900 | N° coffee plants/ha | $4.603^{E7}$ | 5.3 | **0.01** | 7 900 a | 6 900 a,b | 6 000 b | 6 800 a,b |
| **ERSN** | 1.19 | - | 32 | 2.7 | **0.06** | 1.08 a,b | 1.85 a | 0.59 b | 1.22 a,b |
| **AREA** | 2.03 | ha | 124 | 0.1 | 0.98 | 2.0 a | 2.2 a | 1.8 a | 1.9 a |
| **TIME** | 06:50 | hh:mm | -- | 5.6 | **0.01** | 07:40 a | 06:10 c | 06:20b,c | 07:30a,b |
| **YIEL** | 7.1 | t /ha/yr | 31 | 9.0 | **0.00** | 4.2 b | 8.9 a | 7.2 a | 8.1 a |
| **SLOP** | 50 | % | 7 573 | 2.4 | **0.09** | 51 a,b | 49 a,b | 42 b | 63 a |
| **GMAR** | 2 200 | USD/ha/yr | 9 611 329 | 2.9 | **0.05** | 1 300 b | 2 700 a | 2 500 a | 2 500 a |
| **INCO** | 81 | % | 18 405 | 1.1 | 0.36 | 69 a | 89 a | 78 a | 87 a |
| **WORK** | 5.8 | USD/hr | 1960 | 0.5 | **0.08** | 3.9 b | 5.5 a,b | 7.6 a | 6.1 a,b |

Figure 2.1b shows that manual weed cutting was the most time-consuming activity, followed by application of fertiliser and pruning of coffee plants, although the variability between plots was very high.

On the questions regarding perception of erosion, 81% of the respondents thought erosion was a moderate or serious problem in the area, and 53% thought it was a problem on their own farm.

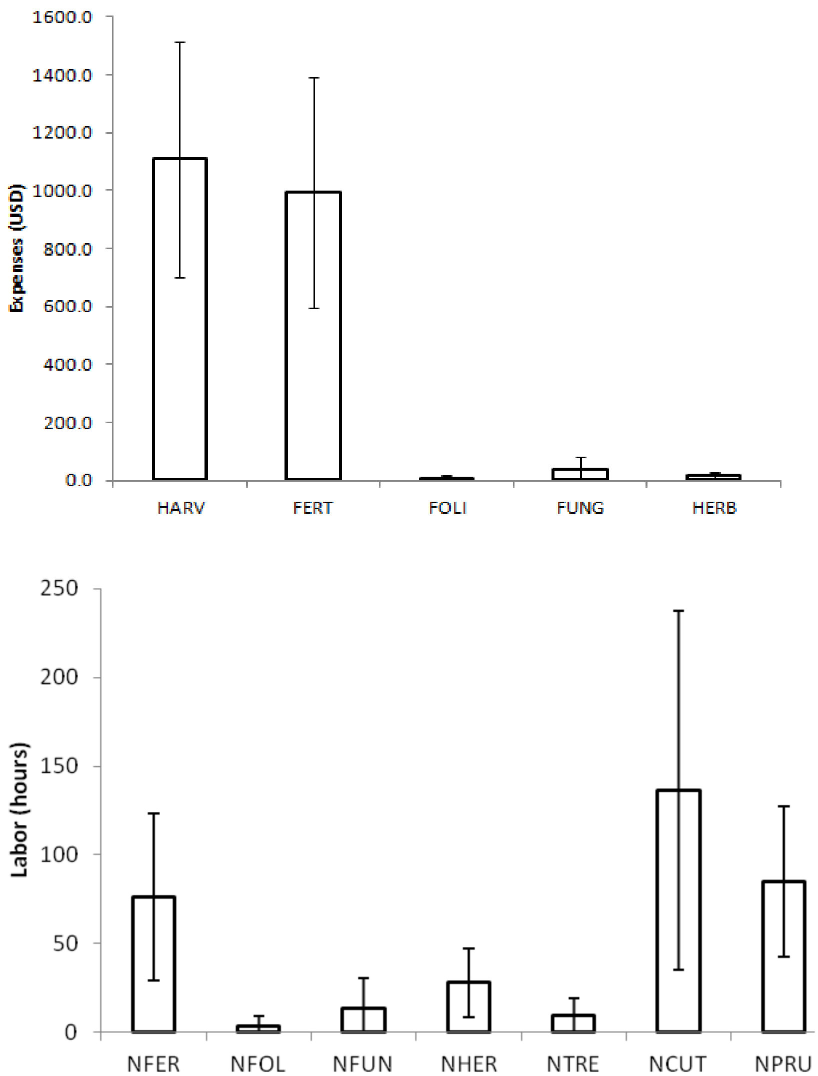



Figure 2.1 – mean cost and labour for each practice : a) USD spent on agrochemicals ; b) hours of labour spent on each practice. Each abbreviation is explained in table 2a.

### *2.3.2 TYPOLOGY*

Following the Principal Components Analysis (PCA) of all management variables (see Table 2a), the first three axes were selected, explaining 54% of the variance. The distribution of the groups on each of these axes is shown on figure 2.2a and 2.2b. These axes were used for the Aglomerative Hierarchical Cluster (AHC) to yield four distinct groups.

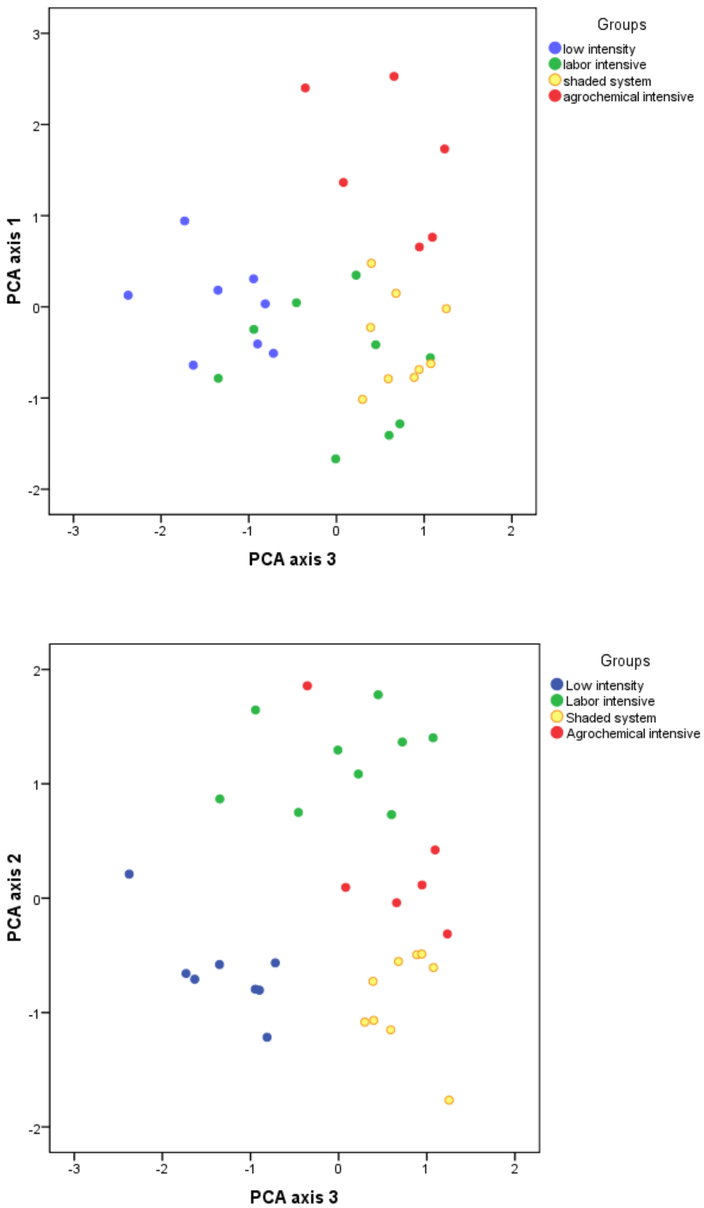



Figure 2.2a and 2.2b – axes 1 and 3 and 2 and 3 of the PCA showing the position of plots of different groups on the three different axes.

Means of the management variables, as well as means of the additional descriptive and contextual variables, are presented for each group in Table 2.3. Overall, significant differences were found between groups in the variables that were used to create them, which was expected. However, significant differences were also found in the descriptive variables that were not used in the PCA, notably in the time of sunrise, yield, and gross margin.

### *2.3.3 GROUPS DESCRIPTION*

Group 1 (low intensity) had consistently lowest use of agrochemicals (subtotal of 576 USD/ha/yr in table

3, versus almost the triple for group 2, for example). It was also the group with the highest rate of owners having another source of income than coffee farming ($INCO_1$ = 69%) and the lowest profit gained per hour of work ($WORK_1$ = 3.9 USD/hour). Significantly less fertilizer was applied ($FERT_1$ = 518 USD/ha/yr) and smaller yield ($YIEL_1$ = 4.2 t/ha/yr) than all the others groups. FERT and YIEL were very significantly correlated for all plots, with an $R^2$ of 0.54 (figure 2.3). Plots in group 1 had the latest time of sunrise ($TIME_1$ = 7:40 am), signifying a more westerly slope orientation. Gross margin was the lowest in this group ($GMAR_1$ = 1 300 USD/ha/yr), while coffee plant density was the highest ($COFF_1$ = 7 900 plants/ha).

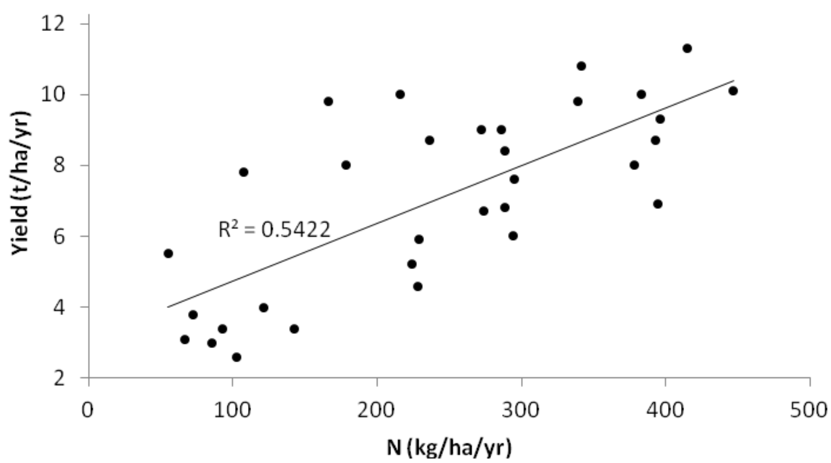



Figure 2.3 – Relationship between coffee yield and N fertilizer applied on each plot (All plots included)

Group 2 (labor intensive) was characterized by significantly higher levels of fertilizer use ($FERTI_2$ = 1 395 USD/ha/yr) and by higher yield ($YIEL_2$ = 8.9 t/ha/yr) than groups 1 and 3. This group also had the most hours of total work (1 432 hours/ha/yr) than any other group, as shown in table 3. Gross margin was also the highest of all groups ($GMAR_2$ = 2 700 USD/ha/yr). In contrast, herbicide used ($HERB_2$ = 5 USD/ha/yr) and hours spent applying it ($NHER_2$ = 13 hours/ha/yr) was significantly lower than groups 3 and 4. As shown by figure 4, plots in this group had avocado trees more frequently than other groups – avocados have recently been introduced to the region as an alternative or complementary crop to coffee for sale (Ortiz, 2011, personal communication). The average time of sunrise ($TIME_2$ = 06:10 a.m.) was significantly earlier than in groups 1 and 4. They had the highest average anti-erosion score ($ERSN_2$ = 1.85) and the highest number of hours spent pruning coffee plants ($NPRU_2$ = 71 hours/ha/yr), both significantly higher than group 3. However there is no apparent relationship between ERSN and YIEL, nor between ERSN and other management variables.

Group 3 - The variable that most strongly characterized "shaded system" group was higher level of shade tree density ($TREE_3$ = 539 trees/ha). This group also had the most trees within each species category, except for avocado trees (figure 2.4). Total hours of labor and money spent on agrochemicals were significantly lower than the labor intensive group, yet yield and gross margin were not significantly different and profit per hour worked ($WORK_3$ = 7.6 USD/hr) was the highest for all groups.

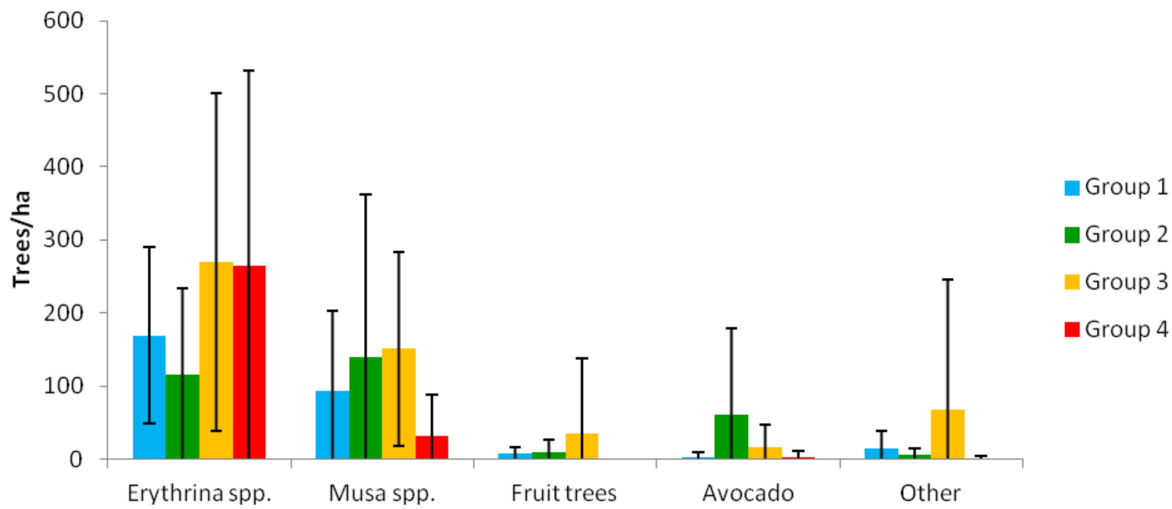



Figure 2.4 – Tree species present on plots in each group

Group 4 (agrochemical intensive) was characterized by a late sunrise ($TIME_4$ = 7.30 am) and a much higher intensity of labor and agrochemical usage than groups 1 and 3 (1 286 USD/ha/yr and 411 hours/ha/yr respectively). Tree density was the lowest of any group ($TREE_4$ = 235 trees/ha), and mostly composed of Erythrina species (figure 3), known for its role as a shade tree favorable to coffee growth and production and that can be pruned easily if needed -for example in case of a strong Mycena attack. They also had, on average, the steepest slope ($SLOP_4$ = 63%) which was significantly higher than that of group 3.

### *2.3.4 TRADE-OFF BETWEEN PRODUCTION AND SHADE TREES*

Figure 2.5 shows the relationship between shade tree density, used as a proxy for soil conservation, and coffee yield. This relationship varied from group to group - the “labor intensive” and “shaded system” groups in particular showed an inverse linear (almost convex-shaped) relationship, with an $R^2$ of 0.301 and 0.565 respectively. Plots in these groups maintained high yield values for low to moderate shade tree densities. On the other hand, in the “low intensity” and “agrochemical intensive” groups, yield appeared to decline as soon as shade tree density increases slightly, indicating a stronger-trade off in a more unfavorable situation.

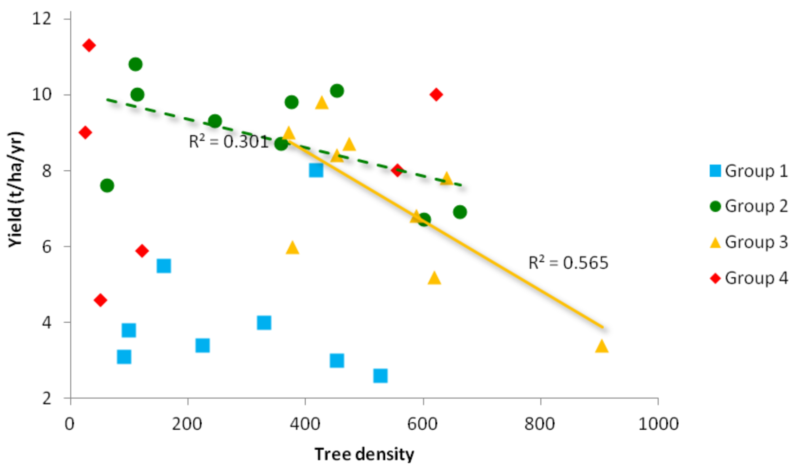



Figure 2.5 – Relationship between yield and shade tree density for different groups

### 2.3.5 CONCEPTUAL MODEL

In the first phase of constructing the model (figure 2.6), exterior factors affecting the coffee AFS were chosen. Agricultural practices mentioned by the farmers in the interviews were divided into practices affecting the coffee plant, the trees, and the soil and water resource management. The model also included non-controllable environmental factors affecting the AFS, divided into physical plot characteristics and climate.

The output factors chosen were sediment loss, which serves to measure the provision of the ES "mitigation of soil erosion"; and yield and gross margin, which were identified as two key performance aspects determining the farmer's livelihood (Ortiz, 2011, personal communication). The components of the AFS were chosen in order to relate processes from the active environment through to the outputs; for example, weed management options affect presence of weeds; and presence of weeds affects vegetative cover and nutrient availability; etc. Each process is summarized in Table 2.4, with the corresponding source of information.

This first version of the conceptual model was then **adapted** to represent the major processes and constraints for each group of plots from the typology (figures 2.7a, 2.7b, 2.7c and 2.7d for groups 1, 2, 3 and 4 respectively) and better describe the diversity of practices and conditions in the area and understand their consequence on the trade-offs between coffee production and soil erosion. The main highlights of each model version are summarized below.

Group 1 "low intensity" - Plots in this group had unfavorable climatic conditions (higher humidity caused by west-facing slopes) that caused incidence of Mycena fungus. There was also no or little control of weeds, which may be explained by low mineral availability and/or lack of time. Application of fertilizer would increase nutrient availability in the soil, giving the weeds more resources for growth. There was no active management of soil erosion, although high coffee density and lack of weed management did have a positive effect. Very low gross margin and profit per hour worked showed a major constraint in lack of labor and funds for improving system performance.

<u>Group 2 “labor intensive”</u> - Plots in this group had the highest level of agrochemical and labor use. High erosion score indicated soil conservation was taken into account in the management strategy. In order to compensate a low density of shade trees, coffee plant health was maintained by a high level of fertilization (N supply) and good soil cover for soil humidity and water infiltration. The plots in this group which did have more shade trees also had lower yields (figure 5). Coffee plants were highly fertilized which caused high levels of fruit node and cherry production. High rate of allocation of resources to the cherries decreased leaf growth, causing branch dieback and higher rates of coffee pruning.

<u>Group 3 “shaded system”</u> – good environmental conditions with gentle slope and good sunlight, and yield and gross margin only slightly lower than group 2. Expensive practices such as fertilizer use and manual weed cutting were avoided while cheaper ones like herbicide application were higher than in other groups. As with other groups, shade trees were still pruned twice a year to increase sunlight at key moments, specifically, during coffee flower production and cherry growth and maturation. Gross margin was closer to the intensive groups while labor hours were closer to low intensity group.

<u>Group 4 “agrochemical intensive”</u> - Plots in this group were similar to group 1 in environmental conditions with Mycena, but similar to group 2 in management intensity. Increased Mycena incidence (augmented by high mineral availability and vegetative growth) was compensated by increased fertilization and foliar fertilization which overcome loss caused by Mycena since yields remained high. Higher slopes gave this group higher potential for erosion problems yet little or no erosion control practices were put into place. In contrast to this, 80% of the farmers in this group thought erosion was a serious problem. Higher reliance on herbicide than on manual control for weed removal indicated non-labor intensive practices may be favored.

Table 4 – Processes included in the conceptual model and sources of information.

Sources of information:

1. Literature; a) Ataroff and Monasterio b) Avelino (2005), c) Babbar and Zak (1994), d) Cannavo et al. (2011), e) Rebolledo (2008), f) Siles et al. (2010), g) Nygren (1995), h) Youkhana and Idol (2009), i) (DaMatta, 2004)

2. Technicians; a) Ortiz, 2011, b) Melendes, 2010 (personal communications)

3. Farmers; a) Castro, 2010, b) Abarca, 2010, c) Duran, 2010, d) Jimenez, 2010 (personal communications)

| **Subject** | **Processes and interactions with other components** | **Source of information** (1,2 or 3 with details) |
|---|---|---|
| Coffee density | Increased biomass and vegetative growth per surface area; at higher densities vegetative growth is favored over cherry production | 2: a<br>3: a |
| Renewal of coffee plants | Increases production since young plants are more productive | 2: a |
| Fungicide spraying | Control attacks by *Mycena fungus* | 2:a<br>3:b |
| Frequency of tree pruning | Decreases overall tree biomass, shade and total litter produced over a year | 1: g, h<br>3: c, d |
| Density of shade trees | Higher tree density leads to increased shading, more fixation of N for *Erythrina* spp, more soil litter and nutrient availability, higher rate of water infiltration in the soil, preservation of water availability during dry season) and lower runoff and erosion | 1: a, d, f<br>2: a<br>3: a, c |
| Shaded area | Increased humidity and decreased solar radiation in plot microclimate | 1: g<br>2: a |
| Chemical fertilization | Increases nutrient availability, which increases both coffee and weed growth; very high levels of fertilization lead to high rates of cherry growth relative to vegetative growth | 2: a |
| Manual weed cutting | Temporarily reduces weed cover but weeds grow back faster than with herbicide, resulting in a higher nutrient competition between coffee and weeds; preserves a vegetative cover on soil and living root web that maintains the soil and reduces erosion | 1: a<br>2: a<br>3: c |
| Herbicide use | Removes weeds for longer periods of time thus increasing nutrient availability; removes soil cover, which increases runoff | 3: a |
| Use of pruning residues for making terraces | Increases soil cover and obstacles to runoff, reduces erosion, facilitates harvest, requires additional labor at the time of pruning | 2:b<br>3: a |
| Coffee vegetative growth | Higher vegetative growth increases plant biomass and development of fruit nodes. Good vegetative growth (especially leaves) is essential for sustaining flower and cherry production. | 3: d |
| *Mycena fungus* | Attacks coffee leaves and cherries, decreases leaf area for photosynthesis and thus vegetative growth, number of fruit nodes, and cherry growth | 1: b<br>3: b |
| Nutrient availability | Increases coffee vegetative growth and cherry growth | 2: a |
| Weeds | Increases vegetative cover of soil; decreases mineral availability due to competition for nutrients | 1: f |
| Litter / vegetative cover on soil | Vegetative material – both live and litter – increases infiltration of water in the soil and evapotranspiration; decreases runoff | 1: f |
| Water infiltration | Increases soil water availability and decreases runoff | 1: a<br>2: b |

| | | |
|---|---|---|
| Runoff | Increases erosion | 2: b |
| Erosion | Increases sediment loss | 2: b |
| Water content (in the soil) | Increases vegetative growth | 2: b<br>3: a, c |
| Number of fruit nodes | Increases number of flowers produced; however, excessive fruit node growth relative to vegetative growth can result in insufficient resource allocation for vegetative growth, resulting in branch dieback | 1: e<br>2: b<br>3: c, d, i |
| Number of flowers | Increases number of grains produced | 1: e |
| Cherry growth | Coffee cherries increase in number and in size; increases total coffee production | 1: e |
| Sediment loss | Model output; performance variable. Measured in tons of sediment/ha/yr | - |
| Gross margin | Model output; performance variable. Measured in USD/ha/yr | - |
| Coffee production | Model output; performance variable. Measured in kg of dry coffee/ha/yr | - |

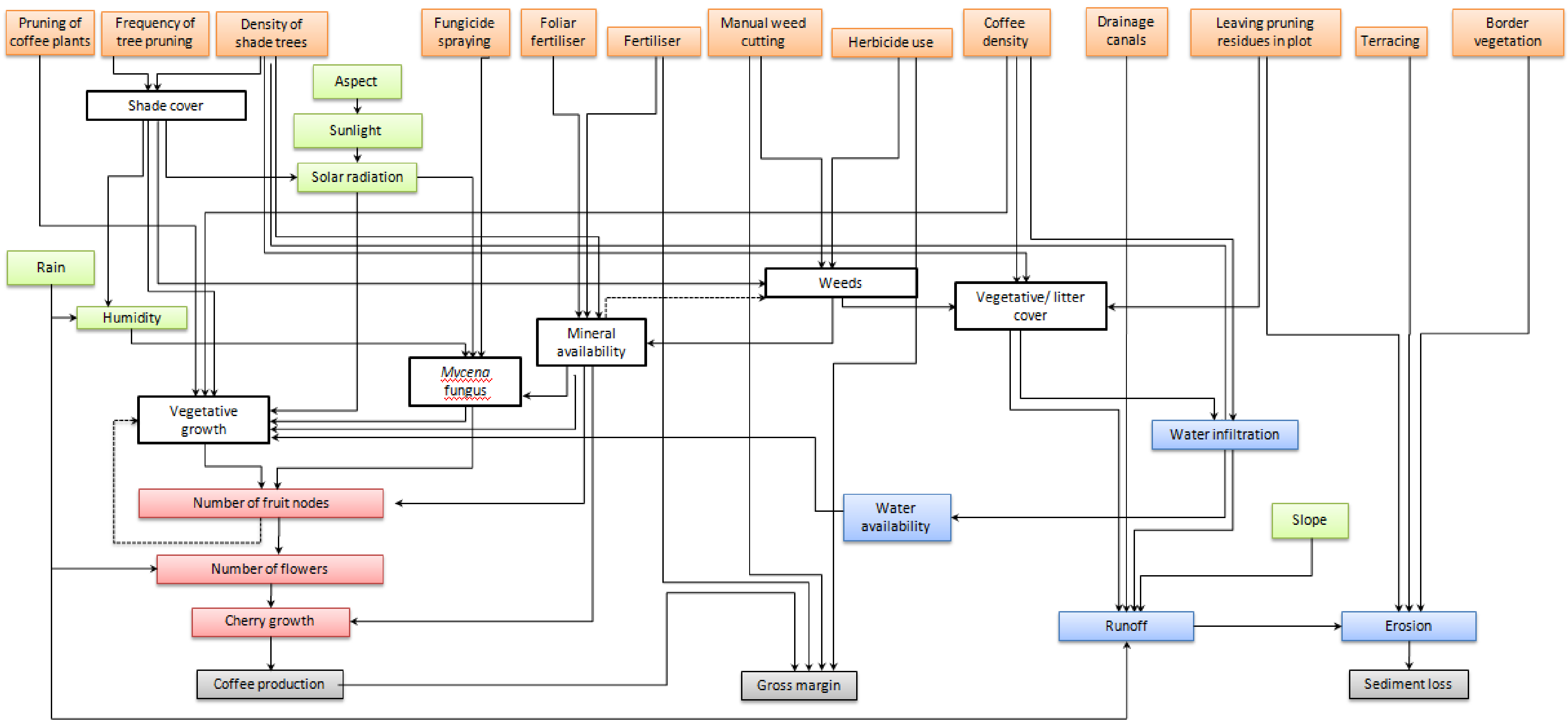



Figure 2.6 – Generic conceptual model of a coffee-based agroforestry system with environmental factors and management practives as inputs, and gorss margin, coffee production and erosion as outputs. Orange boxes are management practices; green boxes environmental factors; dark grey boxes performance outputs; red boxes elements relating to coffee production; blue boxes those relating to water & hrydrological processes. Black arrows indicate that one element has an effect on the other; dotted arrows show a relationship only appearing under certain conditions

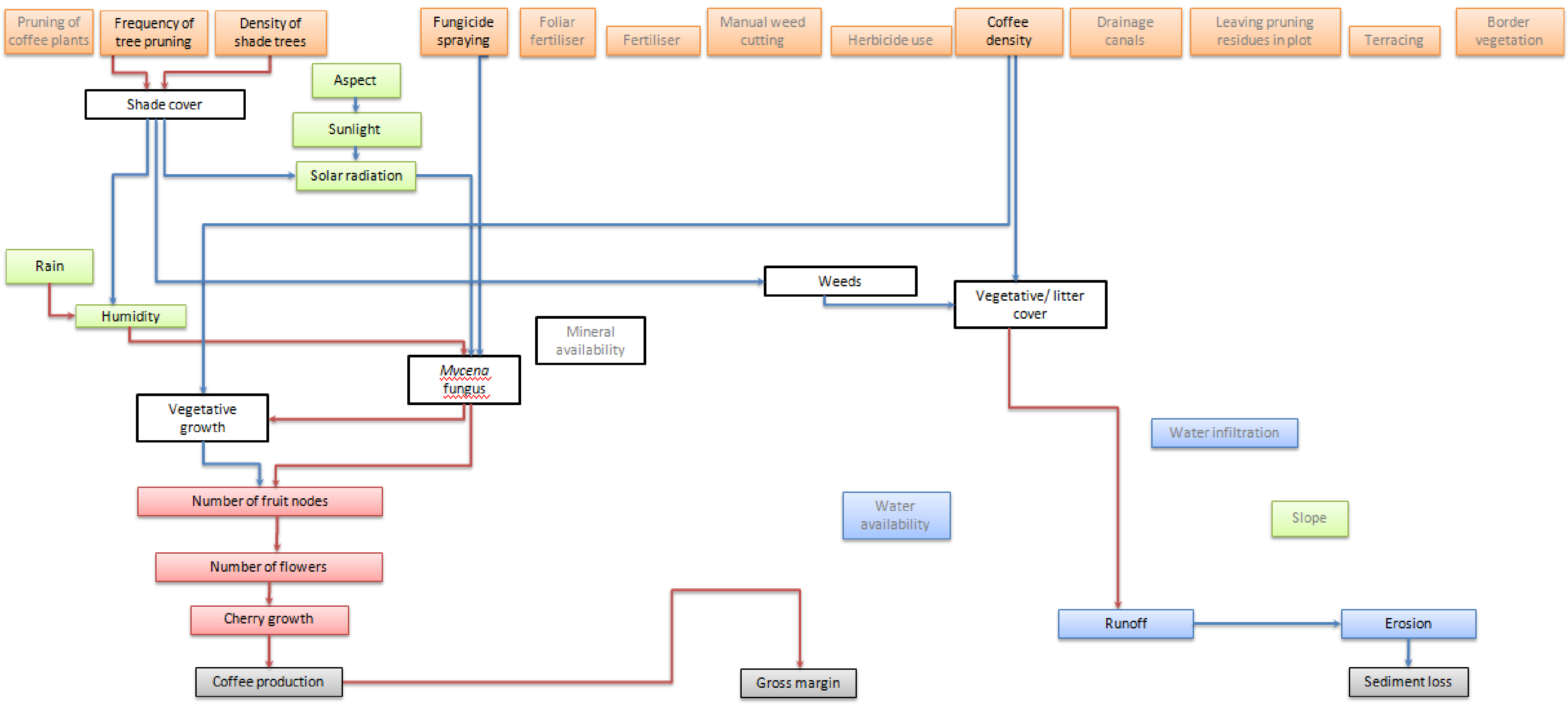



Figure 7a – model adapted for the low-intensity group

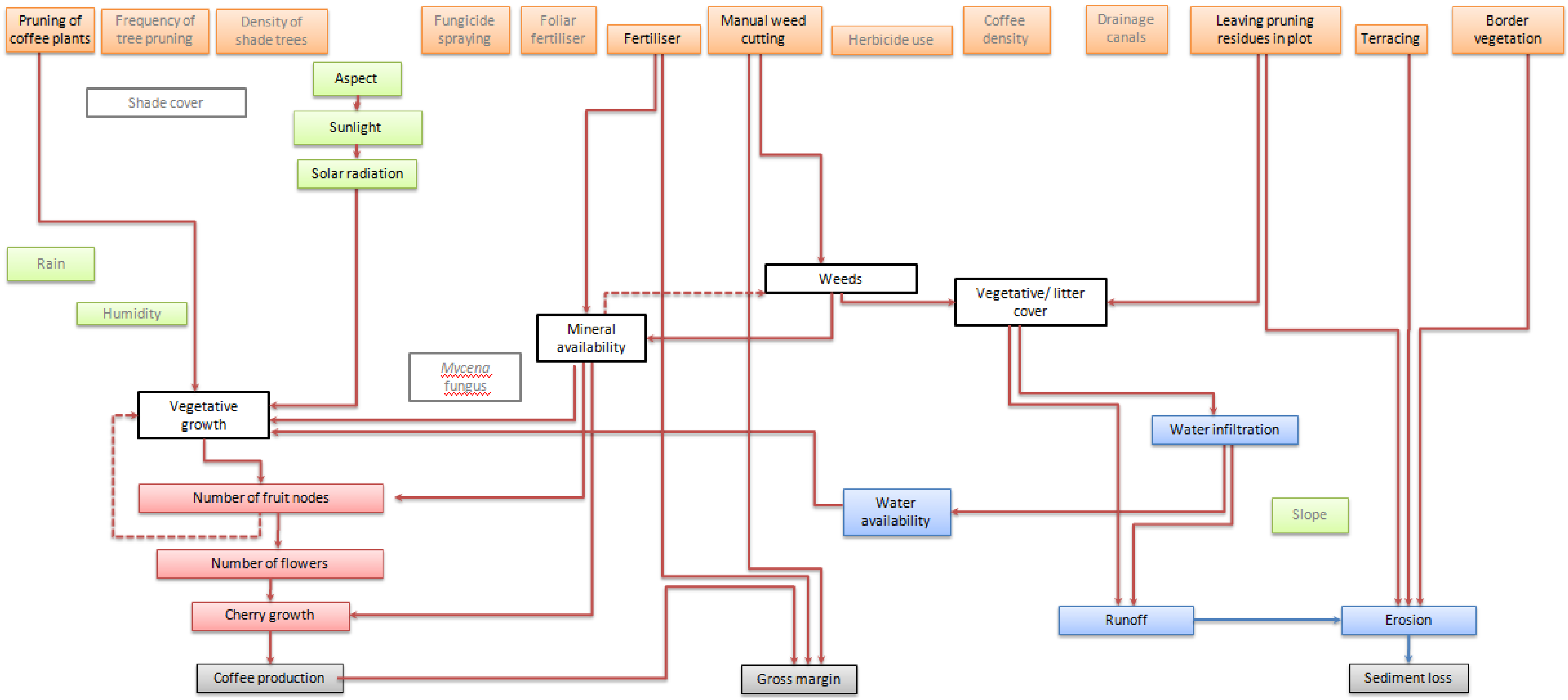



Figure 7b – model adapted for the labor-intensive group

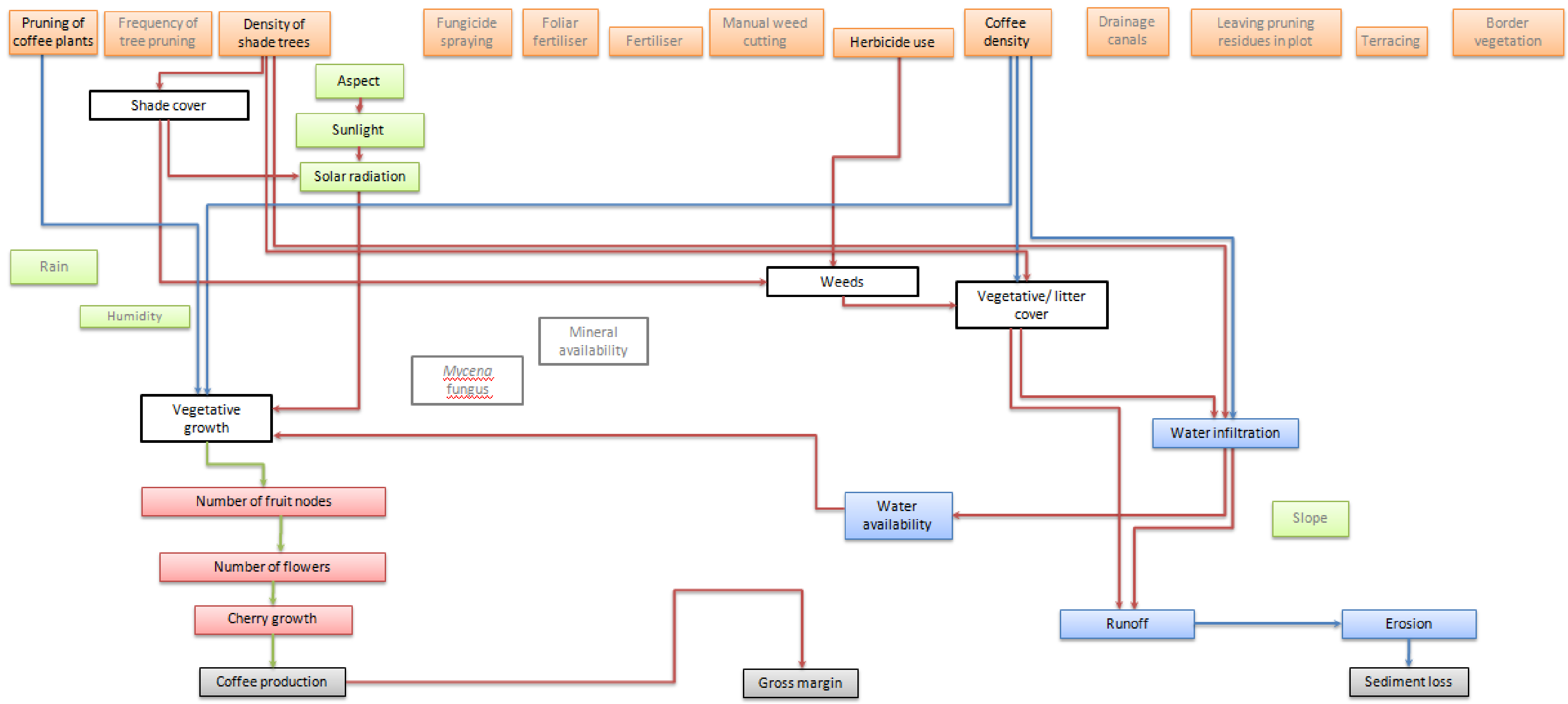



Figure 7c – model adapted for the shaded systems group

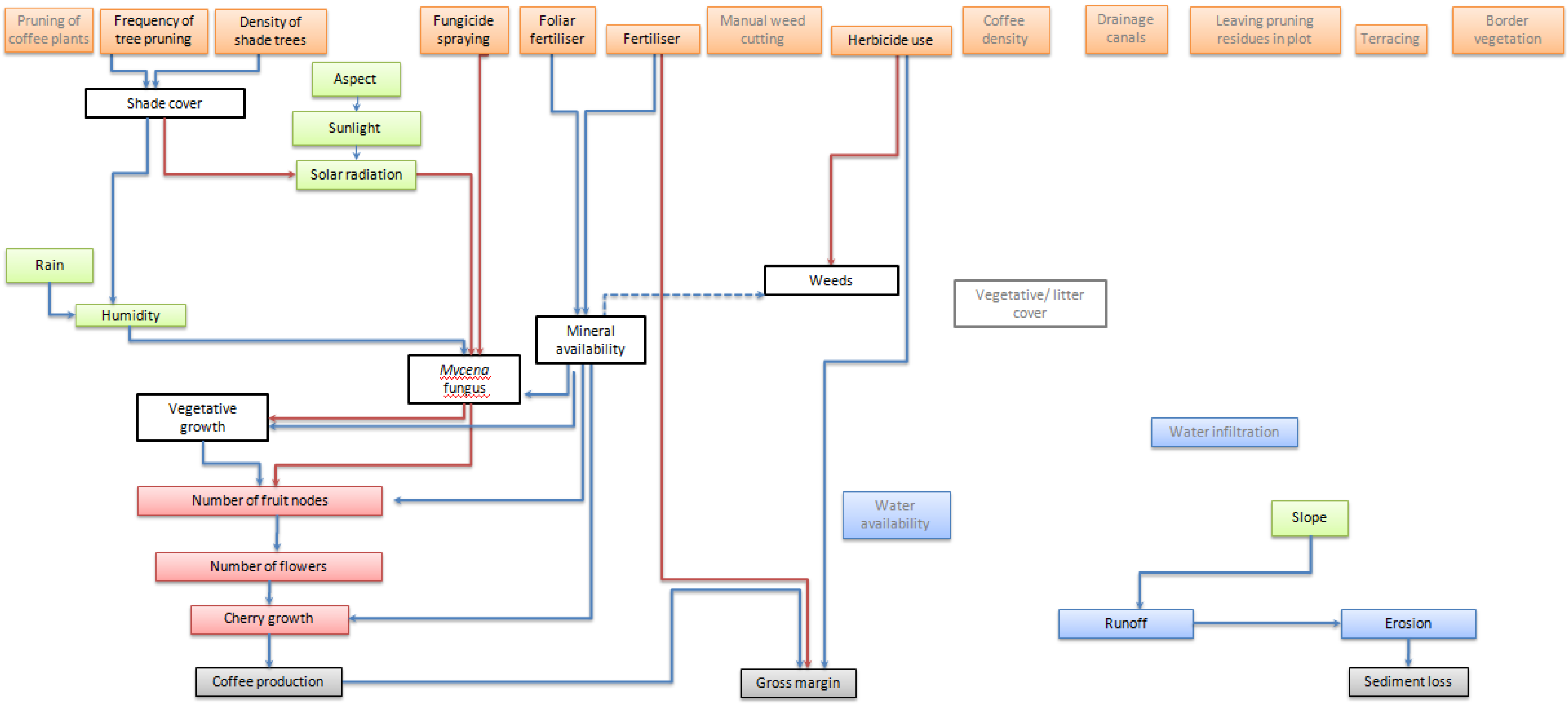



Figure 7d – model adapted for the agrochemical intensive group

## 2.3 DISCUSSION

### *2.4.1 BEST MANAGEMENT PRACTICES TO CONTROL EROSION*

Different conclusions about the best erosion control practices for each group can be drawn from the adaptation of the conceptual model.

Direct erosion control

Direct erosion control methods (vegetative barriers, terraces, etc) require investment in time and labor. Groups with a currently low amount of time invested in managing the coffee plot, such as the low intensity or shaded system groups, may be more open to integrating additional workload. The low intensity group may be particularly receptive to PES schemes for erosion control which would have a stronger impact due to their currently low gross margin and profit per hour worked (Quintero *et al.*, 2009).

Weeds as vegetative soil cover

Leaving a layer of live weeds in the plot as a live soil cover helps prevent erosion (Sentis, 1997), as long as the weeds are regularly cut in order to avoid nutrient and light competition with the coffee plants and making other interventions in the plot physically difficult (Ataroff & Monasterio, 1997). Indeed, the apparent trade-off shown in the model between weeds and coffee production due to nutrient competition appears to be under control as long as weeds are regularly cut (Ortiz, 2011, personal communication). The “labor intensive” group already spends many hours on manual weed cutting, as well as use of pruning residues for terraces, so a good vegetative cover on the soil is likely already assured. It is interesting to note that this is the only group to invest so much time in this activity; yet it is also the group with the highest amount of fertilizer applied. The other intensive group (group 4, agrochemical intensive) appears to favor a combination of herbicide application and manual cutting as their weed management strategy. This study did not explore the complete strategic reasoning behind choices of one management practice over another. However since the labor intensive group also scores highest for erosion control practices used, we hypothesize that there is some recognition of manual weed control as a way of conserving the soil and preventing erosion.

Shade trees and their multiple services

Increasing shade tree density in a coffee plot can bring many benefits to erosion control, such as increased litter, improved soil structure, and decreased impact of rainfall on runoff (Siles *et al*, 2010). The relationship between shade trees, production and erosion is the most complex due to the multitude of functions performed by shade trees, and the one where the conceptual model becomes most useful in helping to understand its variability. The study area presents two distinct microclimates, one in which *Mycena fungus* attacks are occasionally a problem (east-facing slopes) and one where they are consistently an issue, and can cause important yield losses in wetter years (west-facing slopes).

In the first situation, increased shade tree cover appears to have an inverse relationship with coffee yield as shown earlier. The model shows that more shade tree cover may initially decrease coffee yield, due to a decrease in captured solar radiation for photosynthesis. However, the model also highlights that moderating annual coffee cherry production would prevent branch dieback, increasing longevity of the plant and decreasing the need for high levels of coffee pruning. DaMatta (2004) also indicates this strategy allows yields to be more consistent from year to year. This effect is especially apparent in the labor intensive group which spends the most time pruning coffee, while the shaded system group spends the least – both groups with east-facing slopes and dry/sunny microclimate, but the latter with almost twice as many trees than the former. Here, a more detailed model – possibly a numerical model – would be useful to further quantify these complex relationships and find an "optimal" shade tree level, or to fine-tune adaptive strategies of tree pruning depending on the climatic year.

West-facing plots have a different relationship with shade trees due to much higher humidity conditions. Shade tree density is therefore generally kept low, which may explain the absence of a linear relationship between tree density and yield like in the other groups. The conceptual model highlights in both the low intensity group and the agrochemical intensive group that solar radiation and humidity are critical elements  determining rate of fungal attacks and coffee yield – therefore, increases in shade tree density do not appear possible without hitting this major constraint.

### *2.4.2 CONSEQUENCES FOR AFS PROTOTYPING*

Knowledge gained for facilitating prototyping

Coffee is a perennial crop, but coffee cultivation is subject to rapid changes in market prices as well as climate. When working on innovative cropping systems that respond to these changes, studies and proposed changes must be completed with sufficient speed so that the conclusions are still relevant to the farmers when the time comes to apply them.

The initial phase of data collection extended over eight weeks in November/December 2009. This was repeated in February/March 2011 in order to account for yearly variations in practices as well as biannuality of coffee production. Data from a second year was thus used to improve accuracy of the data and avoid bias caused by unusual phenomenon, such as a recent renovation of the coffee plantation. However, a separate typology for years 1 and 2 showed that only 15% of the plots changed group from one year to the next, showing that the similarities between plots in one group remain mostly constant. If the reliability of yield data and other practices if good enough, one session of data collection may be sufficient to gain a data set representative of usual farming practices.

Including practices data in the model construction also helped build an accurate representation of the diversity of systems, despite being in a situation where reliable data on practices was not always available. Farmers do not usually keep a written record of yield, labor hours or agrochemical expenses – especially in developing countries. Nevertheless, working with quantitative data allowed for a more objective analysis of practices. Interviews on farmer decision-making can bring complementary data that can help capture the factors that affect farmers' management strategies.

Data on ecosystem services

The aim of this study was to obtain a relatively rapid protocol that would pave the way for implementing alternative or adapted cropping systems that respond to the needs of farmers and those of stakeholders interested in decreasing erosion. This would have ideally included an accurate assessment of current and potential erosional risk, which was difficult for several reasons. By its very nature, erosion is difficult to measure punctually or over a short time frame since the bulk of erosion processes happens during strong and unfrequent rainfall events (Boardman, 2006). Rates of sediment erosion at the field scale are highly dependent on rainfall and soil saturation rates which vary significantly in a climatic zone marked by alternating dry and wet seasons. In addition to this, erosion studies are generally more relevant at the watershed scale in order to include the effect of pathway and river networks (Gómez-Delgado *et al.*, 2011). Not all plots will have the same susceptibility to erosion due to a number of physical, environmental and management factors. The model designed in this study included several of these factors based on the documented sources of knowledge, such as slope and rain as environmental factors, and tree density, terracing, coffee density and weed management as management factors. With this information we were able to use several variables as proxies for erosion management (e.g. the erosion control practice score). Obtaining additional information would have required direct field measures with extensive sampling in time and in space (Ataroff and Monasterio, 1997), which was not within the scope of this study. Plots were evaluated for existing erosion management practices and not severity of the problem. Furthermore, although the erosion score was not linked to slope, there was a slight correlation between erosion score and erosion perception, hinting that farmers' actions regarding erosion management may be more dependent on their own views than actual environmental conditions. Considering no plot had a slope lesser than 32%, all of the plots sampled had at least some potential risk for erosion during the wet season.

<u>Prototyping and development of a numerical model</u>

New cropping systems are designed to meet specific objectives but also need to inspire enough confidence from the farmers that their implementation will yield significant benefits. An adapted model that identifies the constraints of different groups of plots with common practices can be a platform for future group work. The adapted model can be used in interaction with the farmers to test the validity of the analysis of trade-offs and constraints (Lamanda *et al.*, 2011), and as a basis for evaluating the effect of changes to the cropping system (Whitbread *et al.*, 2009). Using a model as a reference to agronomic discussions could also facilitate communication with technicians and extentionists.

In terms of scientific analysis, conceptual models present the advantage of being able to represent reality without limiting ourselves to what processes we can and cannot measure. The focus is on understanding the system, especially the aspects of it that are relevant to our study. Scientific, technical and informal knowledge can be used for its construction. On the other hand, numerical model might bring many advantages such as the ability to produce quantitative outputs, either biophysical or economical, that speak more clearly to farmers who often think in terms of yield or profit on their crop. However they are limited to current advances in numerical modeling in agronomy. Although separate numerical models for many aspects such as coffee for light competition (Medlyn, 2004), effect of certain pests (Rodriguez *et al.*, 2011) including *Mycena* (Avelino *et al.*, 2007a) are available, few models simulate the global coffee plot and all management options. For example the CAF2007 model (van Oijen *et al.*, 2010b) simulates water, C and N cycles as well as shade tree/coffee interaction and plot-scale runoff, but not the effect of pests and weeds, which are implicated in significant trade-offs in this study. Despite these limitations, numerical models have been used successfully in different research contexts for design of innovative cropping systems (Carberry *et al.*, 2002; Rapidel *et al.*, 2006).

Combining a typology and a conceptual model for exploring the relationships between ES has allowed us to pinpoint some of the major constraints and trade-offs, especially regarding the relationship between shade trees and coffee production. Using this method we were able to appraise the diversity of situations that lead to variations in the relationships between ES and facilitated the identification of potential pathways for decreasing soil erosion at the plot scale in the study area. This opens the door to further study on the quantification of these relationships and trade-offs between ES and orients future work on design of new cropping systems.

# CHAPTER 3

# Using a diversity of plant, soil and water-related variables to evaluate the effect of shade trees on coffee

## 3.1 INTRODUCTION

Agroforestry is based on the principle of trees bringing increased benefit to the cropping system. Integrating trees in cropping systems can lead to greater provision of ecosystem services than if the crop was grown on its own (Torquebiau, 2000). However, crop production and other valuable services may also be inhibited by the presence of trees, due to competition for light, water and nutrients, as well as effects on incidence of pests and diseases. The integration of trees in the cropping system, and the modalities of tree management, must therefore be carefully examined in terms of their impact on the ecosystem services concerned.

Coffee is a plant originally grown under dense forest canopy, and most coffee cropping systems require some degree of shade cover, depending on environmental conditions such as altitude, rainfall patterns, and pest and disease incidence (Beer *et al.*, 1998). Estimates for optimal shade cover vary significantly according to the study area, climatic factors, and indicator studied (Soto-Pinto *et al.*, 2000; Staver *et al.*, 2001; Campanha *et al.*, 2004). Currently estimates of ideal shade cover vary between 20 and 65% shade cover, depending on local conditions. For example, Avelino et al (2007b) found that the effect of shade cover on fungus attacks in Costa Rican highland coffee plantations was dependent on the humidity conditions, determined by slope orientation.

Evaluating the effect of shade trees on coffee agrosystems therefore requires taking into account the trees' effect on various ecosystem services. The primary concern of the effect of shade is coffee biomass production and coffee yield (the main provisioning service). It has been shown that shaded coffee plants can have similar rates of photosynthesis but lower bean production, since lower light levels affect development of reproductive organs and may reduce flowering (Campanha *et al.*, 2004). Rebolledo (2008) decomposed coffee yield into several yield components; the effect of shade can be examined on each of these. In addition to yearly yields, shade trees also help production by preventing dieback (from excessive production) (Chaves *et al.*, 2012) which favors long-term cherry production.

Shade trees also affect the water balance of the cropping system. During the dry season, coffee plants tend to have higher rates of evapotranspiration per unit of leaf area where there is less shade (van Kanten and Vaast, 2006).

In Costa Rica, Erythrina trees are a popular species for providing shade in coffee plantations. As a leguminous species, they have been shown to capture atmospheric $N_2$ and store it in the soil in the form of organic compounds in root nodules – a process known as nitrogen fixation (Nygren and Ramírez, 1995). The nitrogen in nodules, upon decomposition, may become available for other plants to use as well. This has been shown to provide additional N supply in coffee plantation (Salas *et al.*, 2001). Nevertheless, in heavily fertilized cropping systems it is uncertain if Erythrina still accomplishes this energy-demanding function due to high amounts of N already present in the system. Erythrina trees still accomplish other common tree services such as improvement of soil structure and increase in organic matter (Lin and Richards, 2007; Tully *et al.*, 2012).

Finally, trees have been linked to decreases in erosion, mainly due to the soil cover provided (Hairiah *et al.*, 2006; Lin, 2010). Erosion is related to runoff, and increased soil cover can improve the structure of the upper soil layer, increasing the rate of water infiltration into the soil, and thus decreasing runoff (Lin and Richards, 2007). On the other hand, Ataroff & Monasterio (1997) found that erosion was not dependent on the presence of trees, but on total LAI of the plot instead. A clear comparison of these variables in shaded and un-shaded areas of a coffee plantation would help ascertain what the actual effect of trees are on erosion and runoff.

The relationship between shade trees and two ecosystem services – coffee production and erosion – is complex and sensitive to local conditions (Meylan *et al.*, 2013). The work in chapter 1 on the typology and conceptual model allowed us to identify potential trade-offs involving shade tree as key factors in system function and management. Therefore, we would like to further explore these relationships using quantitative data from field measurements.

Field data in commercial fields involve inherent difficulties due to practical considerations, not all factors can be measured and it is difficult to find case study where the factor of interest is the only one which varies. In the present case we need data to be able to measure the level of production as well as erosion, and the effect of shade on each. Enough explanatory variables (e.g. management, plot characteristics) must also be measured in order to fully explain the observed difference in between treatments.

In this chapter we aim to investigate whether **shade trees have an effect** on **coffee production, erosion, and the relationship between the two**. We will examine the different results given by studying this question using **field data from the Llano Bonito area, characterized by different types and densities of shade trees.**

## 3.2 METHODOLOGY

### *3.2.1 SITE DESCRIPTION*

The Llano Bonito watershed (described in chapter 1) was used as the location for data collection. Within this 18km² watershed, four distinct sites were selected.

Figure 2.1 shows a map of the watershed and the location of different sites. Sites 1 and 4 were selected for being exactly opposite each other, thus providing a comparison between east and west-facing slopes known to experience different amounts of solar radiation, and therefore different levels of humidity and fungus attacks. Site 2 was situated higher up in the watershed and was also east-facing, and was selected in order to include Erythrina shade systems in addition to the banana shade systems present in site 4. Site 3, facing south, could be considered an intermediary between west and east-facing sites.


Figure 3.1 – map of sites in the Llano Bonito watershed

Within each site between one and three fields were chosen for study, representing a variety of shade systems. Within a given field, subplots of different shade treatments (coffee under Erythrina, coffee under banana or coffee under full sun) were chosen with at least two replicates in each field.

This setup helped provide data that was used for model calibration, as well as providing a basis for comparing the effect of shade treatments within a single field. Table 2.1 summarizes the characteristics of the different sites studied.

Table 3.1 – description of sites and the fields and shade treatments in each one

| Site | Slope orientation | Field | Shade treatments (# of replicates) |
|---|---|---|---|
| 1 | West | Full sun | Full sun (3) |
| | | Erythrina | Erythrina (3)<br>Full sun (3) |
| | | Banana | Banana (2)<br>Full sun (2) |
| 2 | East | Full sun | Full sun (2) |
| | | Erythrina | Erythrina (2)<br>Full sun (2) |
| 3 | South-east | Mixed | Erythrina (2)<br>Banana (2)<br>Full sun (2) |
| 4 | East | Banana | Banana (2)<br>Full sun (2) |

### *3.2.2 COLLECTION OF FIELD DATA*

Collection of field data was centered around obtaining data on shade trees and coffee plants, and soil cover and water content at the field scale. During the limited period of the study, we focused measurement on four topics:

- the effect of shade trees on coffee yield and yield components,
- the effect of shade trees on use of water by the system,
- the effect of shade trees on litter deposition at the soil surface, and of litter on water infiltration rate at the soil surface,
- the N fixation by Erythrina trees on and N uptake by coffee plants.

Yield

For measuring the effect of shade trees on yield, coffee production was measured in more detail, explicating the different yield components:

Coffee cherry production =

Plants/ha

x shoots/plant

x fruit nodes/shoot

x cherries/fruit node

The total number of cherries is then calculated by an average weight of coffee cherry in order to obtain the total yield in tons/ha/yr.

Plant density was measured for each field in all sites. Coffee plants were planted in rows of 0.7 to 1.8 m wide, with 0.6 to 1.2 m distance in between each plant. In each field, three plants were randomly selected and the distance between two adjacent plants and the two adjacent rows was measured. These values were averaged and used to calculate plant density at the field scale.

In October of 2010 and 2011, the average number of fruit nodes per shoot was counted for all shoots in a randomly selected subsample of plants. This was done in all plots for each site; four plants were selected if the plot contained 10-15 plants, and six plants were selected if the plot contained 15-20 plants. The protocol for deciding the amount of plants to select is shown in annex I).

At the same moment, for each shoot sampled, the number of cherries per fruit node was counted on the top two and bottom two branches. The mean was then calculated and used as the “cherries/fruit node” value for that shoot. The protocol for deciding which branches to sample in order to assess the number of cherries/fruit node was based on a complete sampling of fifty plants, spread over four plots – one in each site. The number of cherries per fruit node was measured on all fruit nodes, on all branches, on all the shoots, on all the plants. This gave a precisely measured reference value for the total number of cherries. The averages of various combinations of branches were then tried in order to obtain the most accurate prediction of average cherries/fruit node across all plots. Considering time constraints, a maximum of four branches could be sampled per shoot. In addition to random branch selection, combinations of branches at different heights (e.g. bottom, middle, top of the shoot) were tested. Using the top two and bottom two branches was the method that yielded the most accurate average number of cherries/fruit node, using the exact value measured by counting all the cherries on all the branches as a reference. A detailed description of this protocol and comparison of the various combinations attempted is included in the annex I.

Finally, a random sample of 100 mature (red) cherries was collected in each of the four sites in October, December and January in 2010 (1200 cherries total). These were weighed fresh, then dried for 3 days at 65°c and weighed again, in order to obtain the average dry weight of a single coffee cherry.

Coffee biomass and pruning estimation
In order to estimate the intensity of annual coffee pruning, the volume of the wood biomass of coffee plants was measured every three months in all the plots. The height and diameter of each shoot and stem of each plant was measured. The product of these two measurements (in $cm^3$) for each shoot or stem was summed up in order to obtain a total wood volume for the plant. We assumed a conical shape of the plant stems and shoots. This wood volume was then correlated to biomass based on data from a number of measurements from destructive sampling of coffee plants (see annex I for more information).The number of shoots per plant was also counted each time.

In order to estimate pruning rate, the average wood biomass per plant was calculated for every plot before and after pruning. Sharp declines in wood biomass (between the measurements for February and May) indicated a removal of part of the coffee plant biomass. The percentage of wood biomass lost from one date to the next was used as a proxy for percentage of coffee biomass pruned.

Flowering and cherry loss
In order to assess the effect of different shade treatments on flowering timing and intensity, coffee buds, flowers and fruits were counted between March and May (flowering season) of 2011. Three mature shoots were randomly selected in each plot, and a top, middle and bottom branch marked with a colored cloth. The number of coffee buds and unopened flowers, fully open flowers, and formed fruit (with or without dead flower still attached) was counted on these branches every 2 weeks until the end of flowering season in May. The total number of fruit nodes on each branch was also recorded.

In order to measure loss of cherries in between flowering period and harvest time, the mean number of fruits per node for the whole plot was compared to that same value measured in October (detailed in the protocol above).

Leaf Area Index (LAI)
Leaf Area Index (LAI) is a key variable affecting canopy cover and rainfall interception, which in turn affects erosion (Ataroff and Monasterio, 1997), thus it was measured on a monthly basis. Each subplot was measured using a Plant Canopy Analyzer LAI2000 (LI-COR, Lincoln, NE, USA), previously calibrated on another study site with the same variety of coffee plants (Taugourdeau, 2010). The LAI for Erythrina and banana shade trees was calibrated by correlating LAI measures with in-field measurements of total leaf count, and average leaf width. Detailed methodologies can be found in annex I. Due to high slope in all plots, only the 3 most vertical angles were used to calculate light transmittance and then LAI – at a proportion of 0.034, 0.104 and 0.862 for the 0-13°, 16-28° and 32-43° angles respectively.

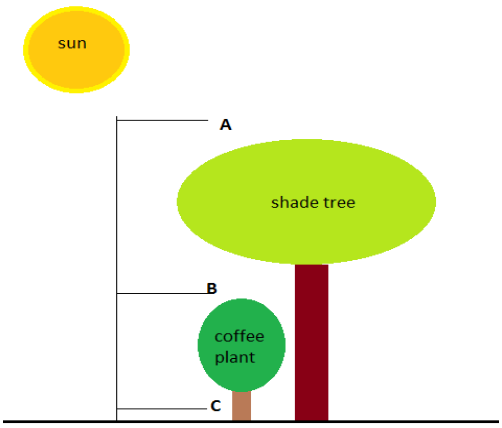



Figure 3.2 – locations of different LAI measurements in the coffee plots

The LAI of coffee and shade trees was measured trimesterly for 2010 and monthly for 2011-2012. As shown in figure 2.2, LAI was calculated by measuring light transmittance values below coffee plants (point C), between coffee plants and tree canopy (point B), and above the tree canopy (point A). The difference in light transmittance A and B corresponded to shade tree LAI, and the difference in transmittance between B and C to coffee LAI.

Evapotranspiration & water infiltration

Pits of 1.5 m depth were dug in plots in the Erythrina shade and full sun monoculture fields in site 1, and in the mixed and Banana shade fields in sites 3 and 4, respectively. One pit was dug per plot to install five Time Domain Reflectometers (TDRs) (Campbell Scientific CS616) connected to a datalogger. Sensors were placed parallel to the soil surface at 15, 30, 60, 100 and 150 cm depth. They were scanned every minute and the average signal (travel time of the reflectometer wave) was stored every 30 minutes. Undisturbed soil samples were extracted to make a laboratory calibration of the TDRs (Udawatta *et al.*, 2011). A detailed account of calibration of the TDRs can be found in the annex I.

Water stocks were calculated for each depth (0-22.5 cm, 22.5-45 cm, 45-80 cm, 80-125 cm and 125-175 cm) in mm by multiplying the measured soil humidity by the volume of soil for $1m^2$.

The daily amount of water lost during the dry season was calculated for periods with at least 3 days without rain to avoid errors related to drainage. Water loss for each soil layer was obtained by subtracting water stocks at 6am from $day^{n+1}$ to the water stocks at 6am on $day^{n}$. Water loss was then divided by the potential evapotranspiration (PET), calculated using the Penman-Monteith equation and site-specific climatic data for each site, using the last FAO guidelines (Allen et al, 1998) (see annex I).

Total LAI values for coffee and shade trees were interpolated in order to obtain total LAI values for the dates at which water loss was calculated. The water loss/PET ratio was then divided by the total LAI for that date in order to compare water loss per area unit of foliage.

TDR values were used differently during wet season, in order to search for differences between shade treatments in water infiltration rates during rainfall events. We used the time lapse it took for water from rainfall to reach the 30cm deep TDR sensor as a proxy for infiltration speed. Assuming the timing of the rainfall recorded in each weather station was homogenous across the whole site, this would allow us to search for differences of infiltration speed between plots with different shade treatments.

In each site, using the rainfall data from the weather station, for each year, we identified 30 “sudden” rainfall events. An event was considered “sudden” if there was at least 12 hours of dry weather, followed by at least 5mm rainfall within one half hour. This eliminated interferences from previous rainfall events (e.g. leftover water still draining) and ensured the amount of water filtering through the soil was important enough to be detected by the TDRs. Looking at the on-site TDR recordings at 30cm depth for that time, we gave a score of 0 to the first sensor(s) that showed an increase in soil water content above 0.003 $cm^3.cm^{-3}$. The sensors showing a significant increase by the next half hour were given a value of 0.5; in the next hour, a value of 1; and so on. The unit for these values was the hour. The inverse of the mean value for each plot over the 30 rainfall events of that year was considered a proxy for the relative speed of water infiltration in that plot.

<u>Leaf Litter</u>
Leaf litter was collected once in June 2011 in all plots, over $2m^2$ in each plot, divided into type of litter (coffee, Erythrina or banana), dried and weighed. The dry weight of litter/$m^2$ was used as a proxy for soil cover.

<u>$^{15}N$ isotopic analysis</u>
We wanted to obtain a very rough assessment of whether Erythrina trees fixed N in the region, and whether this N fixed was used by coffee trees, using the 15N natural abundance technique. To this end, we compared the δ15N of Erythrina trees with those of coffee plants at varying distances from the Erythrina trees.

The $^{15}N$ natural abundance technique relies on the fact that although abundance of $^{15}N$ in atmospheric $N_2$ is constant (Mariotti, 1983) there are small differences in soil and plant N relative to the $^{15}N$ abundance in the atmosphere, expressed as $\delta^{15}N$ or parts per thousand (‰)(Hogberg, 1997):

$$\delta^{15}N(‰) = \frac{1000 \cdot (\text{at\% }^{15}\text{N sample} - 0.3663)}{0.3663}$$

When BNF occurs, the N-fixing legume uses atmospheric N to create usable N reserves at its roots. These reserves will have a lower $\delta^{15}N$ compared to the N supply created through mineralization due to the atmospheric origin of the N (Piccolo *et al.*, 1996). The δ15N of plants can vary substantially according to the plant’s mode of N absorption and other biological factors; however in agroforestry where perennial plants are involved, δ15N tends to be positive, i.e. the abundance of $^{15}N$ in these plants is higher than atmospheric abundance.

In July 2011 (a time of year when shade trees usually have higher levels of foliage), coffee and Erythrina leaf samples were taken from sites 2 and 3 in order to analyze $^{15}N$ content. Due to the potential for spatial variation in $^{15}N$ fixation rates (Stevenson *et al.*, 1995), samples were taken from five different locations in each site. In each location, one Erythrina tree was chosen. There had to be at least 16m between the chosen tree and the next closest tree. A randomly selected of 10 young leaves and 10 mature leaves was taken from the tree. Five coffee bushes were then chosen, at 0, 2, 4, 6 and 8m distance from the tree trunk following a linear transect. In each coffee bush, 10 young and 10 mature leaves were randomly sampled across the whole plant (upper, middle and lower layers). The leaves for each plant (and for each tree) were placed in two separate bags, one for new and one for mature leaves.

Samples were taken on three dates for site 2 (24th June, 5th July, and 15th July 2011) and on two dates for site 3 (25th June and 6th July). Sample collection was timed to avoid application of fertilizer in the 15 days preceding any sampling.

After collection, samples were dried for 2 days in paper bags at 70°C then ground in a mill at 0.2 mm size in order to obtain a homogenous powder. Each sample contained 10 either new or mature leaves from a single coffee plant or Erythrina tree. 3mg of each sample was weighed and packed into a tin capsule. It was then analyzed for $^{15}N$ content using a PDZ Europa ANCA-GSL elemental analyzer interfaced to a PDZ Europa 20-20 isotope ratio mass spectrometer (Sercon Ltd., Cheshire, UK) at the Stable Isotope Facility at UC Davis (USA).

### *3.2.3 ANALYSIS OF FIELD DATA*

The analysis of data was centered on the effect of shade on four groups of variables: a) yield and yield components, b) flowering and grain loss, c) evapotranspiration, water infiltration and soil cover, and d) N fixation. Water infiltration was used as a proxy for runoff, itself a proxy for erosion, since no direct erosion measurements was available.

The effect of shade on variables from these categories was studied using a univariate ANOVA in SPSS 17.0 after checking for homogeneity of variances (or normal distribution of residuals). Yield and all the yield components, flowering intensity, plant and tree biomass and LAI, water stocks and related variables, relative speed of infiltration, and soil litter, were the dependent variables used. Site, field, shade treatment, and coffee plant density, as well as the interactions between each of them, were the fixed factors used in the analysis. A significance threshold of 10% was used.

A more detailed comparison of yield was made in between sites 1 and 2, which both offer a comparison of full sun monocultures and Erythrina-shaded fields on a single site, and therefore identical climate and practically identical management. For each comparison, the average yield for all plots in a) Erythrina shaded fields or b) Erythrina shaded plot was divided by the average yield for a) full sun monoculture on the same site, or b) full sun plots in the same field.

## 3.3 RESULTS

### 3.3.1 CHARACTERIZATION OF YEARS AND SITES

Climate

Table 3.2 presents the average values for climatic variables for the 2010 and 2011 years. Year 2010 goes from March 2010 to February 2011, which corresponds to one growing season (ending with the last of the harvest in February). Year 2011 goes from March 2011 to February 2012. For the sake of simplicity, they are referred to as “2010” and “2011”.

Table 3.2 – average values of climatic variables for 2010 and 2011 in each site

| | Wind (m/s) | | Temperature (°C) | | RH (%) | | Rainfall (mm) | | PAR (mE) | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Site** | **2010** | **2011** | **2010** | **2011** | **2010** | **2011** | **2010** | **2011** | **2010** | **2011** |
| 1 | 0.07 | 0.41 | 18.4 | 18.4 | 89.8 | 85.3 | 3620 | 2190 | 15700 | 16700 |
| 3 | 0.44 | 0.07 | 18.2 | 18.7 | 86.5 | 85.3 | 3830 | 2000 | 16100 | 18100 |
| 4 | 0.54 | 0.43 | 18.7 | 19.1 | 85.9 | 83.6 | 3200 | 1870 | 16600 | 18900 |

The year 2010 was markedly wetter and less sunny than 2011. The year 2010 was exceptionally rainy, with an average of 1530mm more rainfall than in 2011, across all sites. According to farmers, this had significant effects on loss of coffee cherries and incidence of American leaf spot (*Mycena citricolor*).

Management

Every 6 months for 2 years, the owners of the studied fields were asked to describe the agrochemicals they applied, and the timing, length and cost of each operation. Each site was owned by a single farmer, so most farming practices were the same across all fields. The main difference between each field and between plots was pruning intensity; this is presented in the section on yields. A summary of the main farming practices for each site is presented in Table 3.3.

Table 3.3 – summary of main farming practices for 2010 and 2011 in each site

| | Site 1 | | Site 2 | | Site 3 | | Site 4 | |
|---|---|---|---|---|---|---|---|---|
| | **2010** | **2011** | **2010** | **2011** | **2010** | **2011** | **2010** | **2011** |
| Fertilizer applied (kg of N/ha) | 420 | 400 | 290 | 320 | 424 | 449 | 413 | 476 |
| Herbicide applied (L/ha) | 7.52 | 6.58 | 5.94 | 4.54 | 0.61 | 0.80 | 1.55 | 1.49 |
| Fungicide applied (L/ha) | 1.77 | 2.16 | 0.00 | 0.41 | 0.75 | 1.13 | 0.00 | 1.02 |
| Foliar fertilization applied (L/ha) | 2.09 | 2.47 | 1.44 | 1.20 | 0.70 | 0.84 | 0.00 | 0.58 |
| Hours spent on cutting weeds (hrs/ha) | 75 | 70 | 145 | 133 | 138 | 149 | 248 | 185 |

Soil analysis

Soil samples were taken once in June 2011 in each plot at 10, 40, 80 and 120 cm depth, in two locations in each plot: one set of samples taken directly beneath the foliage of a randomly selected coffee plant, and the other at equal distance between two rows of plants. Samples were taken using a 1.5 m soil auger with 4 cm width. Samples were preserved at room temperature and taken to laboratory analysis at most 24 hours after being collected, and were analyzed for total nitrogen and carbon content using a ThermoFinigan FlashEA 1112 autoanalyzer.

Table 3.4 – mean values for total N and total C for each plot, field and site; standard deviation is in brackets

| Site | Field | Shade | Total nitrogen | | | Total carbon | | |
|---|---|---|---|---|---|---|---|---|
| | | | 10 cm | 40 cm | 80-120 cm | 10 cm | 40 cm | 80-120 cm |
| 1 | Full sun monoculture | Full sun | 0.40 (0.06) | 0.20 (0.02) | 0.07 (0.02) | 4.04 (0.74) | 1.97 (0.18) | 0.66 (0.16) |
| | Erythrina shade | Full sun | 0.30 (0.08) | 0.14 (0.02) | 0.07 (0.02) | 2.71 (0.84) | 1.18 (0.23) | 0.58 (0.28) |
| | | Erythrina | 0.29 (0.04) | 0.20 (0.06) | 0.04 (0.01) | 2.64 (0.47) | 1.72 (0.61) | 0.34 (0.10) |
| | Banana shade | Full sun | 0.24 (0.01) | 0.20 (0.00) | 0.09 (0.01) | 2.49 (0.39) | 2.10 (0.05) | 0.74 (0.22) |
| | | Banana | 0.31 (0.01) | 0.13 (0.00) | 0.06 (0.00) | 3.16 (0.07) | 1.23 (0.10) | 0.49 (0.08) |
| 2 | Full sun monoculture | Full sun | 0.29 (0.04) | 0.14 (0.08) | 0.08 (0.04) | 2.85 (0.35) | 1.20 (0.64) | 0.59 (0.29) |
| | Erythrina shade | Full sun | 0.41 (0.05) | 0.30 (0.07) | 0.09 (0.03) | 4.02 (0.46) | 2.85 (0.88) | 0.70 (0.31) |
| | | Erythrina | 0.41 (0.12) | 0.35 (0.01) | 0.16 (0.04) | 4.19 (1.21) | 3.40 (0.20) | 1.26 (0.58) |
| 3 | Mixed shade | Full sun | 0.48 (0.10) | 0.37 (0.08) | 0.12 (0.01) | 5.12 (0.72) | 4.00 (0.44) | 1.31 (0.13) |
| | | Erythrina | 0.39 (0.08) | 0.29 (0.07) | 0.13 (0.04) | 4.44 (0.30) | 3.17 (0.55) | 1.49 (0.51) |
| | | Banana | 0.43 (0.03) | 0.29 (0.00) | 0.12 (0.04) | 5.12 (0.09) | 3.39 (0.28) | 1.43 (0.57) |
| 4 | Banana shade | Full sun | 0.22 (0.10) | 0.20 (0.03) | 0.06 (0.00) | 2.71 (1.07) | 2.39 (0.29) | 0.60 (0.07) |
| | | Banana | 0.13 (0.01) | 0.12 (0.04) | 0.04 (0.02) | 1.58 (0.12) | 1.43 (0.35) | 0.56 (0.27) |

Table 3.4 summarizes the results of the lab analysis. An ANOVA on the total N and C values at different depths (as well as overall average) showed that neither site, field or shade treatment had significant effects on soil N and C content.

### *3.3.2 YIELD*

Table 3.5 – yield estimates for 2010 and 2011 for each plot (standard deviations in brackets)

| Site | Field | Shade treatment | 2010 | | 2011 | |
|---|---|---|---|---|---|---|
| | | | % pruned | Yield (t/ha) | % pruned | Yield (t/ha) |
| 1 | Full sun monoculture | full sun | 3 | 9.49 (3.1) | 49 | 3.58 (2.6) |
| | Erythrina shade | full sun | 8 | 6.07 (2.3) | 36 | 5.30 (1.9) |
| | | Erythrina | 17 | 6.71 (7.6) | 43 | 1.89 (0.5) |
| | Banana shade | full sun | 22 | 2.72 (1.0) | 0 | 6.68 (1.2) |
| | | banana | 27 | 3.47 (1.0) | 0 | 8.22 (4.3) |
| 2 | Full sun monoculture | full sun | 0 | 2.32 (0.4) | 21 | 7.06 (1.4) |
| | Erythrina shade | full sun | 17 | 3.02 (1.0) | 2 | 8.41 (0.0) |
| | | Erythrina | 30 | 3.83 (1.4) | 25 | 4.53 (0.4) |
| 3 | Mixed shade | full sun | 22 | 2.93 (0.5) | 3 | 9.28 (0.7) |
| | | Erythrina | 10 | 4.14 (2.8) | 0 | 6.96 (2.9) |
| | | banana | 26 | 4.22 (1.8) | 42 | 3.25 (3.4) |
| 4 | Banana shade | full sun | 10 | 6.14 (0.1) | 70 | 5.21 (2.0) |
| | | banana | 5 | 10.40 (6.0) | 74 | 2.89 (0.3) |

Table 3.5 shows the global results of yield estimations for each plot for 2010 and 2011, along with the percentage of coffee wood biomass removed 10 months prior to the harvest. An ANOVA on the yield, with site, field and shade treatment as fixed factors, yielded no significant differences.

In order to compare the effect of shade at different scales, we examined the yields for sites 1 and 2 averaged by field and by plot (table 3.6).

Table 3.6 – comparison of yields in sites 1 and 2 (positive ratio indicates yield was higher in Erythrina shade)

| | Site 1 | | Site 2 | |
|---|---|---|---|---|
| | **2010** | **2011** | **2010** | **2011** |
| Yield of Erythrina field / yield of full sun field | 0.67 | 1.00 | 1.47 | 0.92 |
| Yield of Erythrina plots / yield of full sun plots in Erythrina field | 1.11 | 0.36 | 1.27 | 0.54 |

Although for site 2 we observed that coffee yield under shaded systems was higher than for plants under full sun, this observation was reversed in 2011. Furthermore there was no significant difference between any of the comparisons. **Looking purely at yield values, it was therefore not possible to find a significant effect of shade trees on yield.**

### *3.3.3 YIELD COMPONENTS*

A linear regression between each of the variables used to calculate yield (see in methodology) and actual yield value, allowed us to check which yield components were the most important (see table 3.7).

Table 3.7 – linear regression between variables used in calculating yield, and yield itself

| Variable | Equation | $R^2$ |
|---|---|---|
| Mean # of cherries per fruit node | y = 1.42x + 1.28 | 0.11 |
| Mean # of fruit nodes per shoot | y = 0.04x + 1.48 | 0.40 |
| Mean # of shoots per plant | y = 0.39x + 3.38 | 0.09 |
| **Mean # of fruit nodes per PLANT** | **y = 0.01x + 0.30** | **0.85** |
| Plant density | y = 3E-05x + 5.17 | < 0.01 |

The factors with the highest $R^2$, which best explained the variation in yield values, were the mean number of fruit nodes per shoot ($R^2$ = 0.40), followed by the pruning rate ($R^2$ = 0.24). However, combining these yield components by excluding the shoot phase (so mean # of fruit nodes per PLANT) gave us an $R^2$ of 0.85. The number of fruit nodes per plant was therefore the best yield predictor; this slightly simplified structure was kept for the rest of the analyses.

The data appears to suggest two distinct pruning strategies. Plots with low amount of shoots per plant and high number of fruit nodes per shoot, indicating regular pruning in order to keep few shoots that are large and highly productive; and plots with high amount of shoots per plant and low number of fruit nodes per shoot, indicating low rates of pruning and the fruit nodes being spread out across many shoots. These two variables compensated each other, which explains how both the number of fruit nodes per shoot and number of shoots per plant were poor predictors of yield, yet the combination of the two was a very good indicator.

An ANOVA was performed on the yield and its components, with site, field, shade and year as fixed variables. Table 2.8 below summarizes the factors which came out as having a significant effect (at p<0.10) on the different variables tested. Although no single factor had a significant effect on yield directly, the site, field and shade treatments all had an effect depending on the year (i.e. effect of each factor in interaction with the year was significant).

Table 3.8 – summary of ANOVA test results on yield components showing significant effects of a factor on the dependant variable

| **Dependent variable** | **Source** | **d.f.** | **F** | **Sig.** |
|---|---|---|---|---|
| Yield (t/ha) | Site*Year | 2 | 9.81 | < 0.01 |
| | Field*Year | 2 | 3.09 | 0.05 |
| | Shade*Year | 2 | 3.20 | 0.05 |
| Mean # of cherries per fruit nodes | Year | 1 | 3.55 | 0.06 |
| | Site*Year | 2 | 3.06 | 0.06 |
| | Shade*Year | 2 | 4.51 | 0.01 |
| Mean # of fruit nodes per plant | Site*Year | 2 | 10.41 | < 0.01 |
| | Field*Year | 2 | 3.49 | 0.04 |
| | Shade*Year | 2 | 2.42 | 0.10 |
| Plant density | Site | 2 | 374.42 | < 0.01 |
| | Field | 2 | 21.83 | < 0.01 |
| % of pruned offshoots | Site | 2 | 7.93 | 0.02 |
| | Year | 2 | 14.30 | 0.01 |
| | Site*Year | 2 | 19.15 | < 0.01 |
| | Field*Year | 2 | 6.98 | 0.03 |

Site and field had significant effects on plant density; site 1 had the highest average plant density (7773 plants/ha) and within site 1, the Erythrina shaded field had an even higher density (8467 plants/ha). Coffee plant density was mainly the result of farmers' decision at the time of planting, and varied little with plant regeneration since old plants are simply progressively replaced with new ones in the same space.

The ANOVA showed that year, site*year and shade*year had significant effects on the mean number of cherries per fruit node. Indeed, the mean number of cherries per fruit node for all sites was significantly higher in 2011 (3.08) than in 2010 (2.77), as confirmed by a paired student's t-test (P=0.09). When looking at the performance of different shade treatments for each year, we noted that Erythrina shaded plots had slightly higher mean number of cherries per fruiting node than full sun plots in 2010 (2.89 and 2.61 respectively) but this was reversed in the following year (2.63 and 3.17).

Shade*year also had significant effects on the number of fruit nodes per plant. Banana plots had more fruit nodes than full sun plots in 2010 (473 and 428 respectively), but the reverse was observed in 2011 (381 and 547). The number of fruit nodes per plant was less variable from year to year for Erythrina shaded plots, showing only a small increase from 403 in 2010 to 434 in 2011.

Yield in Erythrina shaded plots only decreased from 2010 to 2011 in the plots in the Erythrina shaded field in site 1 (from 6.71 to 1.89 t/ha) – in all other sites and fields, yield actually increased but was overshadowed by the even stronger increase of the full sun plots to which they are compared (in site 2, from 3.83 to 4.53 t/ha; in site 3, from 4.14 to 6.96 t/ha).

These marked differences in the effect of farm, field and shade treatment factors from year to year, are accompanied by a significant difference in climate (2010 being a much wetter year) as well as percentage of coffee pruned, which also strongly varies according to the year and the farm (farms 1 and 4 having a significantly higher pruning ratio in 2010, which occurs 9 months before the 2010 harvest).

Overall, variations in yield and in yield components was strongly linked to annual variations in yield caused by climate, pruning, as well as natural variations in coffee yield. Coffee tends to present a biannual oscillation on yield: a high yield one year is supposed to trigger a lower yield the next year. This is due to a stress on reserves, which provokes die-back or trigger increased coffee pruning by the farmer (Chaves *et al.*, 2012). A linear regression between the 2010 and 2011 yields gives an $R^2$ of 0.25 ($F=8.86$, d.f. 1, $P=0.01$) appears to confirm this relationship (see figure 2.3 below).

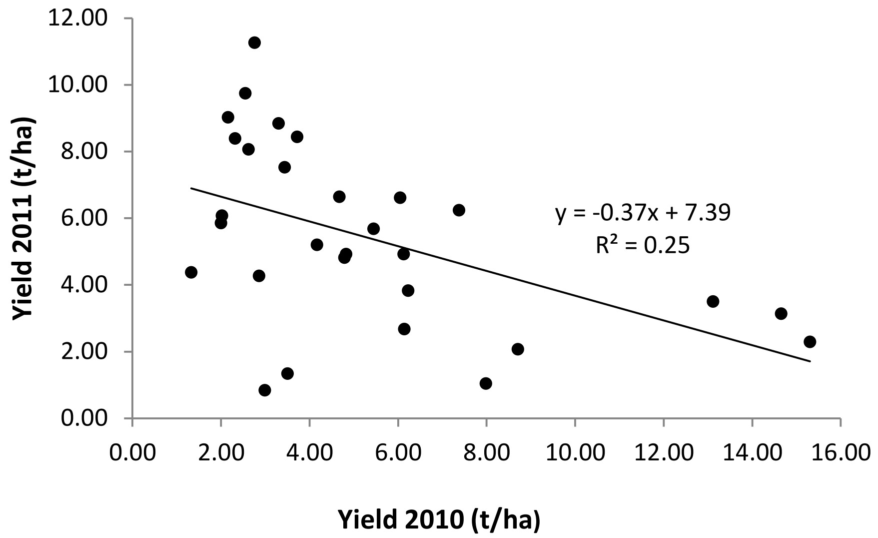



Figure 3.3 – inverse relationship between yield of each plot in 2010 and 2011

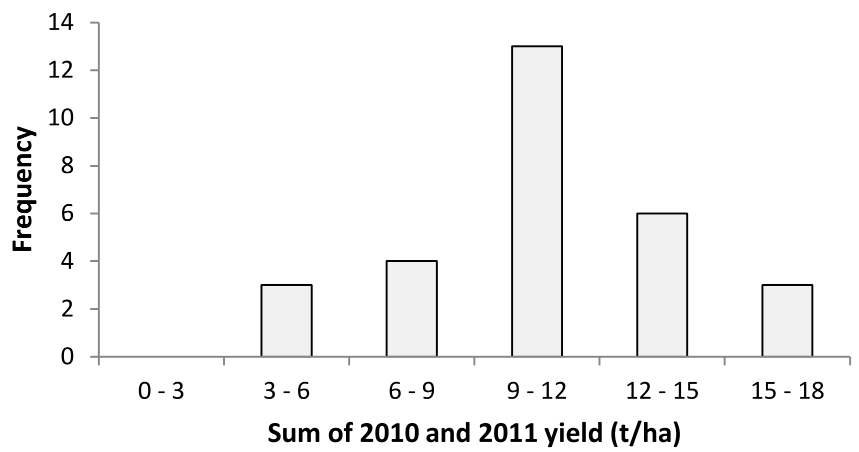



Figure 3.4 – histogram of the values for 2010 and 2011 yield summed up

There appears to be an inverse relationship between the yields of the two successive year ($R^2=0.25$); furthermore, although some plots had low yields both years, no plot had high yields both years. A histogram of the frequency of the values for 2010 and 2011 yield summed up (figure 3.4) shows that they are normally distributed.

Since the biannual oscillation was not homogenous across farms or fields, this may well explain the interactions observed previously, while both factors have no separate effects on yields. **We were therefore not able to detect any consistent effect of shade on coffee yield nor coffee yield components.**

### *3.3.4 FLOWERING*

Table 3.9 shows the flowering intensity and loss of coffee cherries per fruit node between the end of the flowering season and the beginning of the harvest period. The loss of coffee cherries is compared to the total production of cherries/m² (an indicator of yield) as well as the mean coffee LAI for 2010.

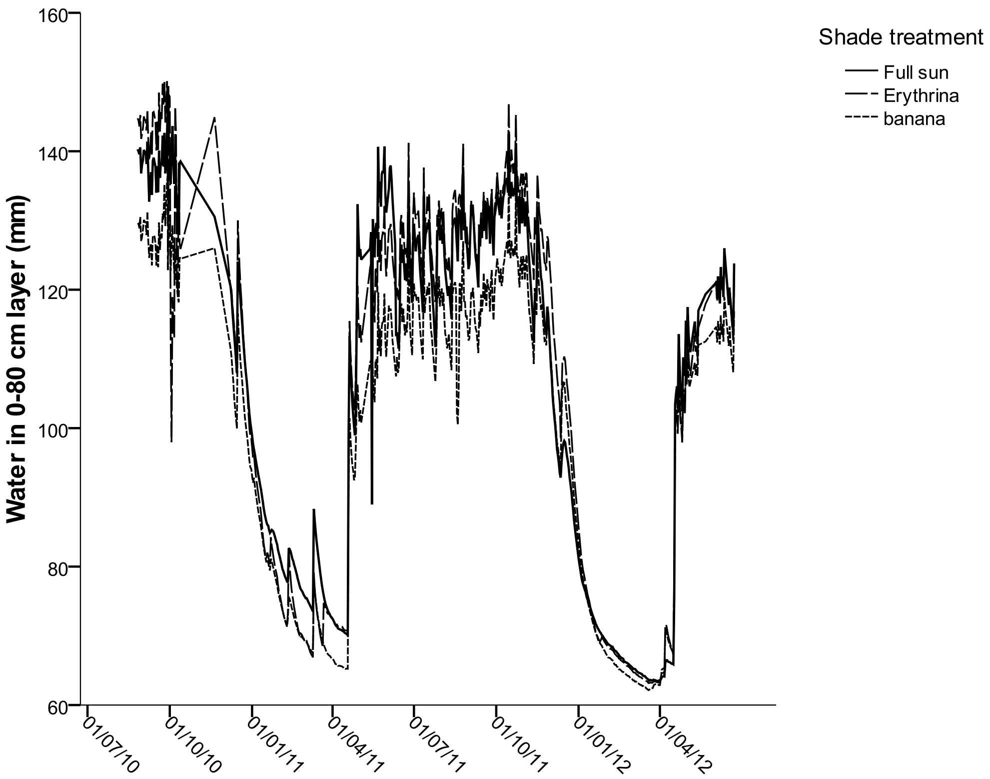
Table 3.9 – flowering intensity, cherry loss, and LAI during flowering and harvest season in 2010 – standard deviation is in brackets where means were calculated

| Site | Field | Shade treatment | Cherries/node after flowering | Cherries/node before harvest | Difference | Cherries/m² | Coffee LAI (wet season 2010) |
|---|---|---|---|---|---|---|---|
| 1 | Full sun | Full sun | 5.08 (1.0) | 2.48 (0.2) | 2.60 | 1530 (510) | 5.04 (0.3) |
| | Banana | Full sun | 7.05 (0.8) | 2.33 (0.1) | 4.72 | 440 (160) | 3.54 (0.2) |
| | | Banana | 4.90 (0.6) | 2.34 (0.4) | 2.56 | 560 (160) | 3.00 (0.7) |
| | Erythrina | Full sun | 6.48 (1.0) | 2.19 (0.3) | 4.29 | 980 (370) | 5.22 (0.8) |
| | | Erythrina | 5.20 (0.2) | 2.31 (0.3) | 2.89 | 1080 (1210) | 4.47 (0.3) |
| 2 | Full sun | Full sun | 7.94 (0.3) | 2.49 (0.1) | 2.33 | 370 (70) | 4.01 (0.2) |
| | Erythrina | Full sun | 5.79 (0.1) | 2.59 (0.2) | 6.33 | 490 (160) | 3.44 (0.1) |
| | | Erythrina | 4.37 (0.2) | 3.66 (0.8) | 2.93 | 620 (220) | 4.12 (0.2) |
| 3 | Mixed | Full sun | 9.20 (0.2) | 2.30 (0.9) | 6.74 | 470 (90) | 2.76 (0.9) |
| | | banana | 6.89 (0.3) | 2.70 (0.4) | 4.49 | 670 (450) | 3.62 (0.3) |
| | | Erythrina | 7.52 (0.8) | 2.38 (0.9) | 4.54 | 680 (280) | 3.74 (0.1) |
| 4 | Banana | Full sun | 8.27 (0.5) | 3.89 (0.2) | 5.37 | 990 (20) | 2.47 (0.2) |
| | | Banana | 6.55 (0.6) | 4.28 (0.3) | 2.26 | 1680 (970) | 3.37 (0.4) |

The loss of cherries appeared to be almost always higher in plants under full sun, compared to Erythrina or banana shade – except in site 2 where loss of cherries in the full sun field was less than the loss in the neighboring Erythrina field. However, the plots in the full sun field also had a very low yield that year (see table 2.5). There was no significant relationship between cherry loss and the total number of cherries/m² or coffee LAI during the wet season ($R^2$ of 0.05 and 0.13 respectively). However, a linear regression showed that the # of cherries/node after flowering and LAI were significantly correlated with an $R^2$ of 0.26 (d.f. 1, $F = 9.43$, $P < 0.01$).

### *3.3.5 EVAPOTRANSPIRATION*

Figures 3.5a and 3.5b show the evolution of water stocks at shallow (15-60 cm) and deep (100-150 cm) depths for 2010 and 2011, for different shade treatments in the two sites where humidity sensors were installed and humidity data was calibrated. We observe some differences; for example that water stocks for plots under banana shade are overall lower than full sun or Erythrina shaded plots in site 3, but they are overall higher than full sun plots in site 4.



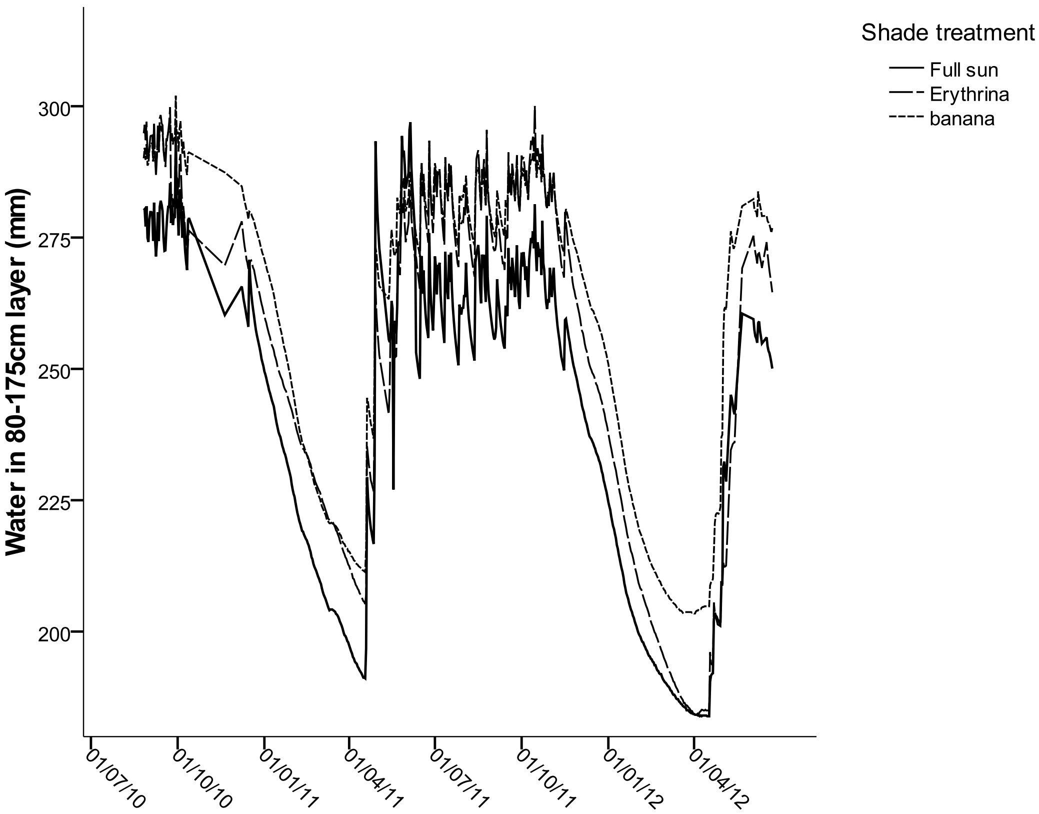
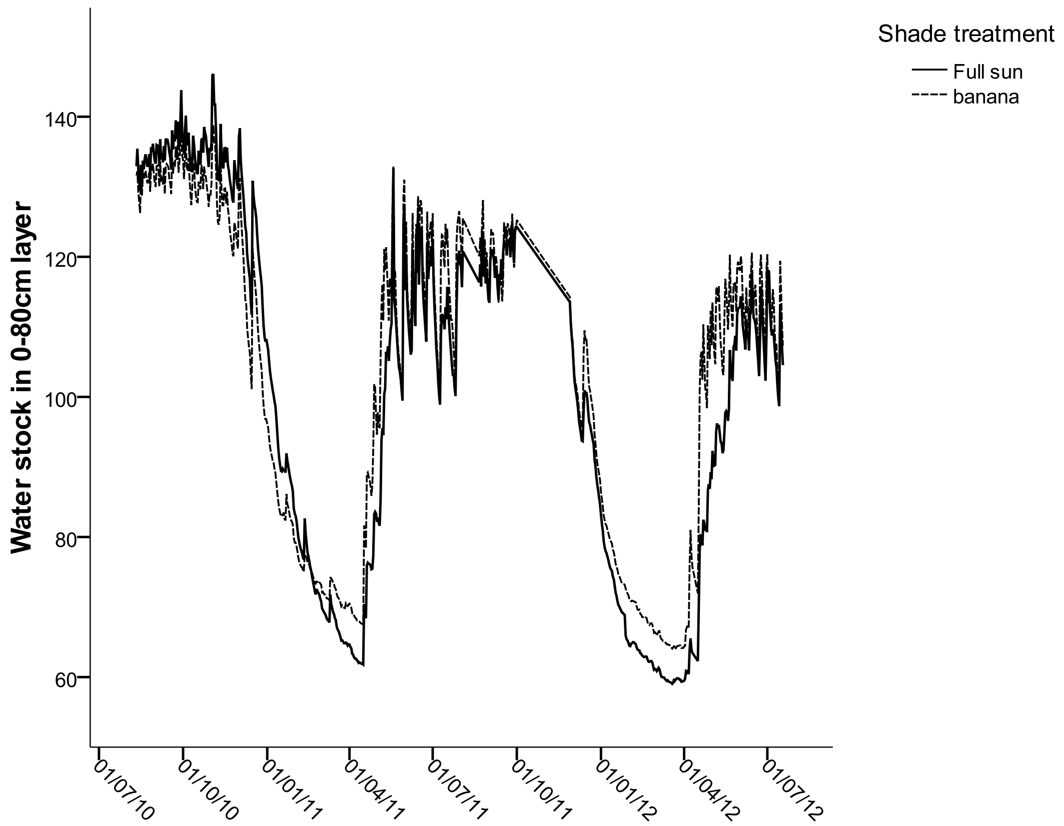




Figure 3.5a – water stocks for site 3



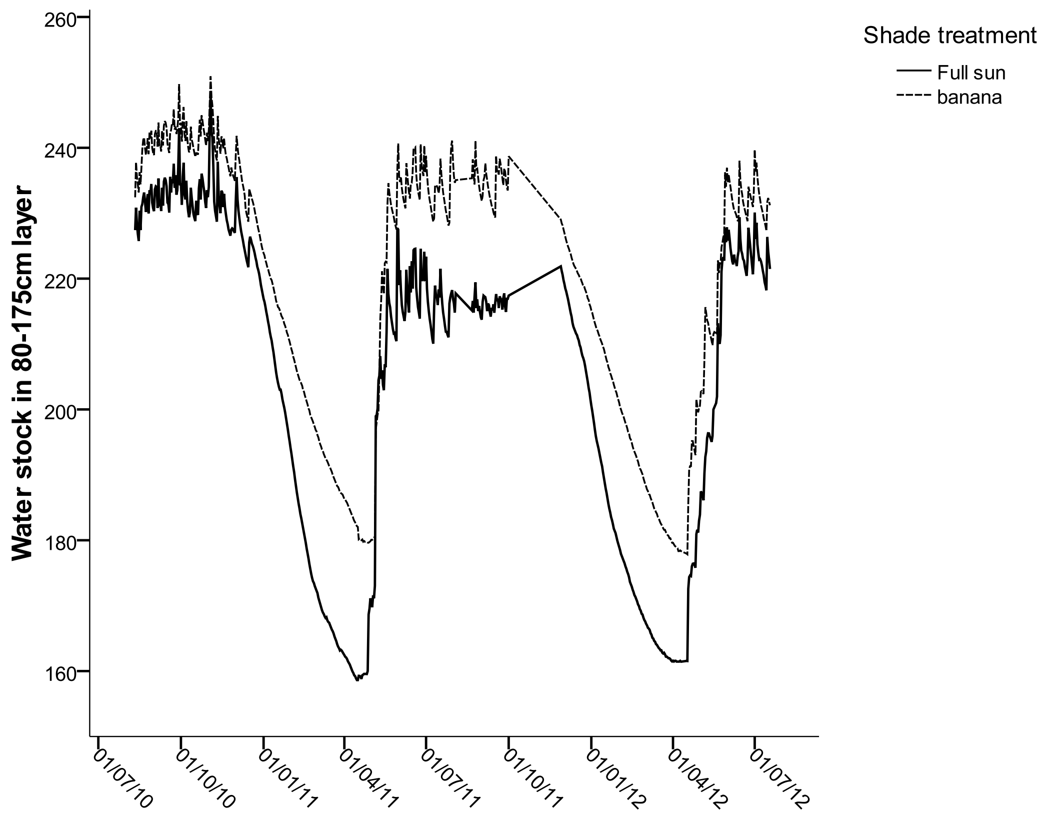
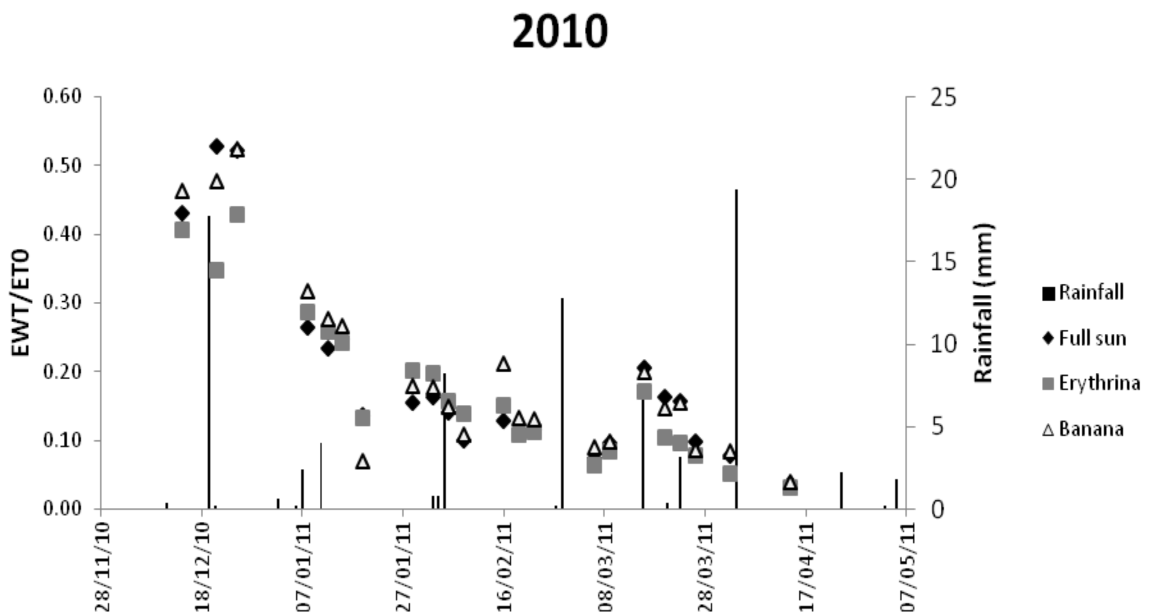




Figure 3.5b –water stocks for site 4



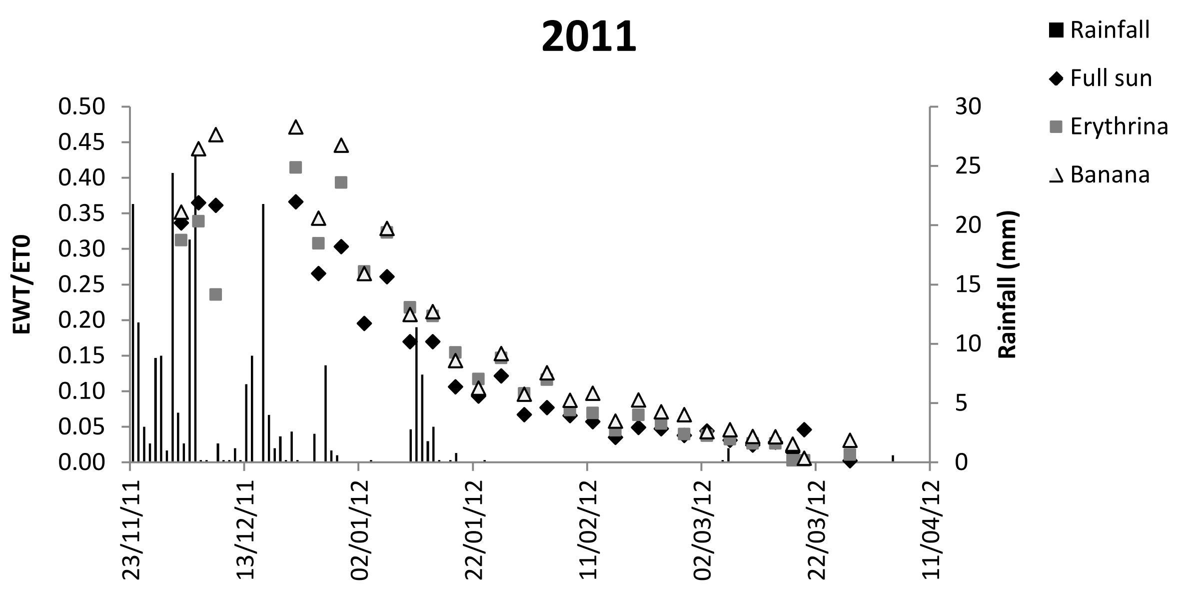




Figure 3.6 – evapotranspiration rates for different shade treatments in site 3, with rainfall, for 2010 and 2011

We examined more closely the evapotranspiration rates of different shade treatments in site 3, which offered a direct comparison of plots under Erythrina shade, banana shade and full sun. Figure 3.6 above shows the differences in relative water loss (evapotranspiration EWT /potential evapotranspiration ET0) for 2010 and 2011. The two years are different in that 2010 has occasional rainfall throughout the dry season, while in 2011 there is no rainfall from mid-January till mid-April. There appears to be little significant difference between the different shade treatments, although plots under full sun appear to conserve slightly more water at the beginning of the dry season in 2011. However, this was not necessarily related to shade trees; coffee LAI under Erythrina (from 2.77

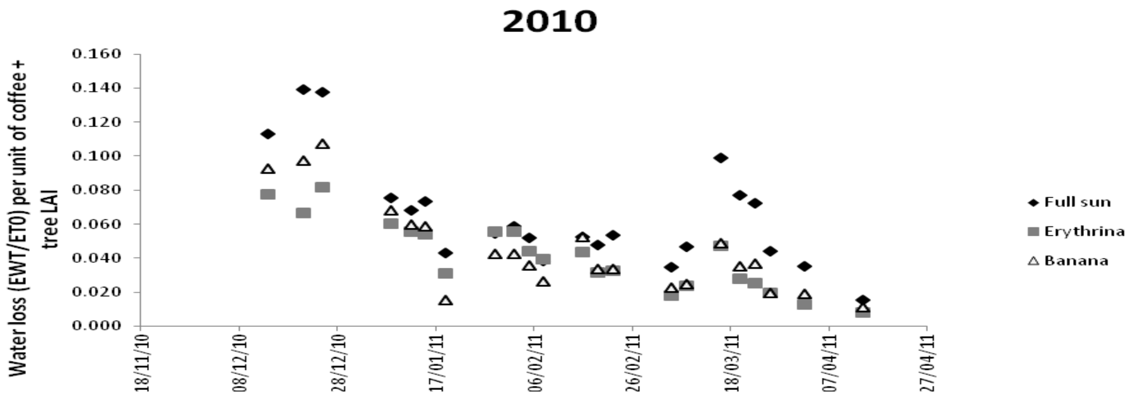
to 4.84) and banana shade (from 3.14 to 4.86) was higher than coffee LAI under full sun (from 1.82 to 3.85) – as shown in table 3.10.

Table 3.10 – summary of LAI maximum and minimum during wet season for 2010 and 2011 (month indicated under each value)

| Plot | LAI Coffee | | LAI Erythrina | | LAI Banana | | LAI total | |
|---|---|---|---|---|---|---|---|---|
| | max | min | Max | min | max | min | max | Min |
| Full sun | 3.85<br>Nov | 1.82<br>Mar | - | - | - | - | 3.85<br>Nov | 1.83<br>Mar |
| Erythrina | 4.84<br>Nov | 2.77<br>Mar | 1.32<br>Jan | 0.26<br>Mar | - | - | 5.98<br>Feb | 3.24<br>Mar |
| Banana | 4.86<br>Aug | 3.14<br>Mar | - | - | 1.13<br>Nov | 0.00<br>- | 5.35<br>Nov | 3.56<br>Mar |

Strong pruning of banana trees mid-2011 caused banana tree LAI to drop to nearly 0 for the remainder of the study. In both Erythrina and banana plots, coffee LAI was always higher than tree LAI due to frequent pruning, tree heights in the study area do not exceed 3m.

In order to account for possible effect of the LAI on evapotranspiration, the EWT/ET0 for each plot was divided by the LAI of all species interpolated for each sample date. Figure 2.7 below shows the result of this for site 3 for 2010 and 2011.



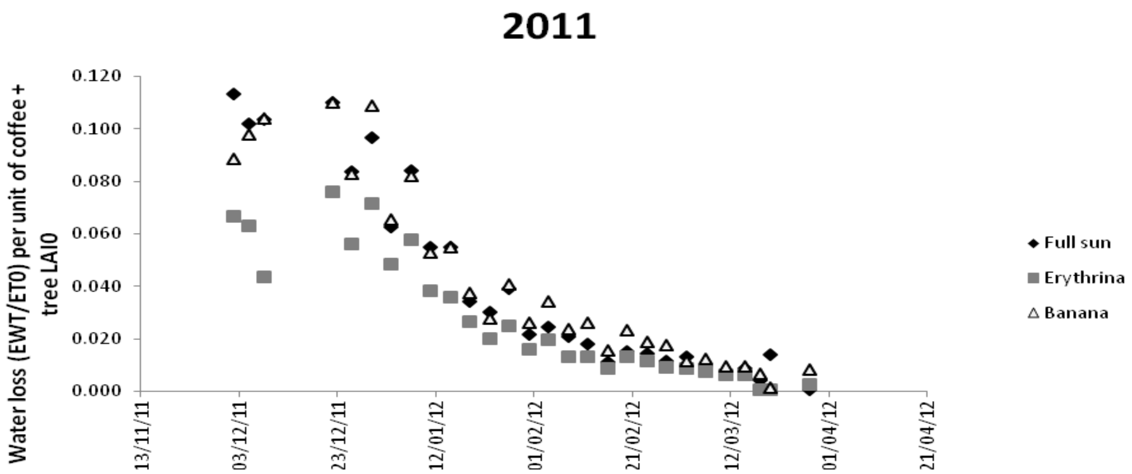




Figure 3.7 – relative water loss per unit of total LAI for different shade treatments on site 3, for 2010 and 2011

In contrast from the graphs showing ETR/ET0, plots in full sun show noticeably higher levels of water loss per unit of LAI in 2010, especially at the start of the dry season. Rainfall events in early 2011 cause the difference in water loss to increase again (see figure 2.6). In 2011, both full sun *and* banana-shaded plots show higher water loss than Erythrina plots. However, banana tree LAI from August 2011 to 2012 does not exceed 0.02, so in for the dry season of 2011 plots under banana shade, in reality, are exposed to full sun. Plots without shade appeared to lose slightly more water per unit of leaf area than plots with shade, during the beginning of the dry season or shortly after rainfall. The LAI in shaded plots is shared between coffee and tree leaves, while the total LAI in full sun plots is only coffee. This may indicate that coffee plants transpire more than shade trees, proportionally. By the end of the dry season or after very long period without rainfall, there was no noticeable difference in evapotranspiration rate for between shaded and unshaded plots. The end of the dry season (March) also corresponds to the moment when Erythrina shade trees have the least foliage (shown in Table 2.10).

Photosynthesis on coffee and tree leaves was not measured; therefore water stress could not be directly assessed – but considering figures 2.3 and 2.4 which show very little difference between shade treatments, it is likely that water stress at the end of the dry season was the same across all plots (with a highly reduced evapotranspiration rate). **Therefore, it appears that shade treatment overall had no significant effect on evapotranspiration.**

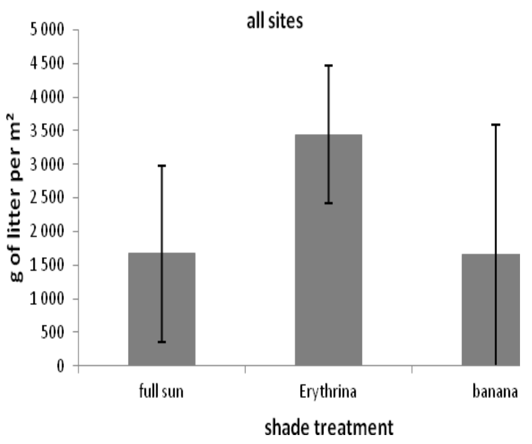
### *3.3.6 WATER INFILTRATION AND LITTER*

On average, full sun plots had 1.7 kg of litter per m², against 3.4 kg for Erythrina shade plots (see figure 3.8). Plots under banana shade showed a much higher variability and did not have any significant difference with either full sun or Erythrina plots. However, there were significant differences between Erythrina and full sun plots. An ANOVA showed that field and shade treatment had significant effects on the amount of litter per m² (see table 3.11).

We observed a significant relationship between amount of litter/m² and relative speed of water infiltration in the soil (figure 3.10 below). The $R^2$ (of all series together) was of 0.70. Additionally, plots under Erythrina shade had significantly lower infiltration delay than plots under full sun treatment (see figure 3.9). This indicated a potential correlation between amount of litter and infiltration delay, modulated by shade treatment. **Overall it appeared that plots under Erythrina shade had more litter and faster infiltration than plots under full sun.**

Table 3.11 – ANOVA results for effect of site, field and shade treatment on litter and infiltration delay

| | **Litter** | | | **Infiltration delay** | | |
|---|---|---|---|---|---|---|
| | d.f. | F | Sig. | d.f. | F | Sig. |
| Site | 2 | 0.06 | 0.94 | 0 | - | - |
| Field | 2 | 3.01 | **0.07** | 1 | 0.53 | 0.48 |
| Shade treatment | 2 | 4.43 | **0.03** | 2 | 6.72 | **0.01** |
| Site*Field | 1 | 0.15 | 0.71 | 0 | - | - |
| Site*Shade | 2 | 1.24 | 0.32 | 0 | - | - |



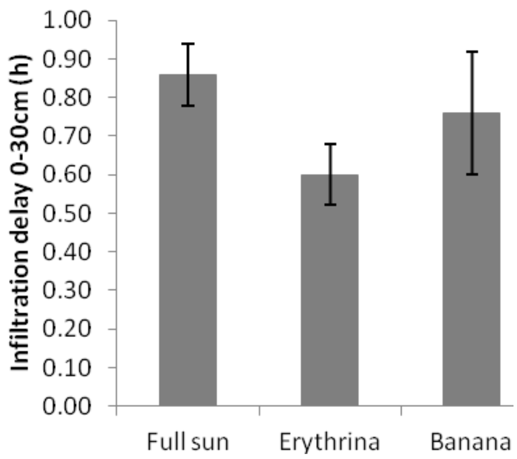




Figure 3.8 – average amount of litter for different shade treatments across all sites in 2010

Figure 3.9 – infiltration delay for different shade treatments on site 3, for 2010

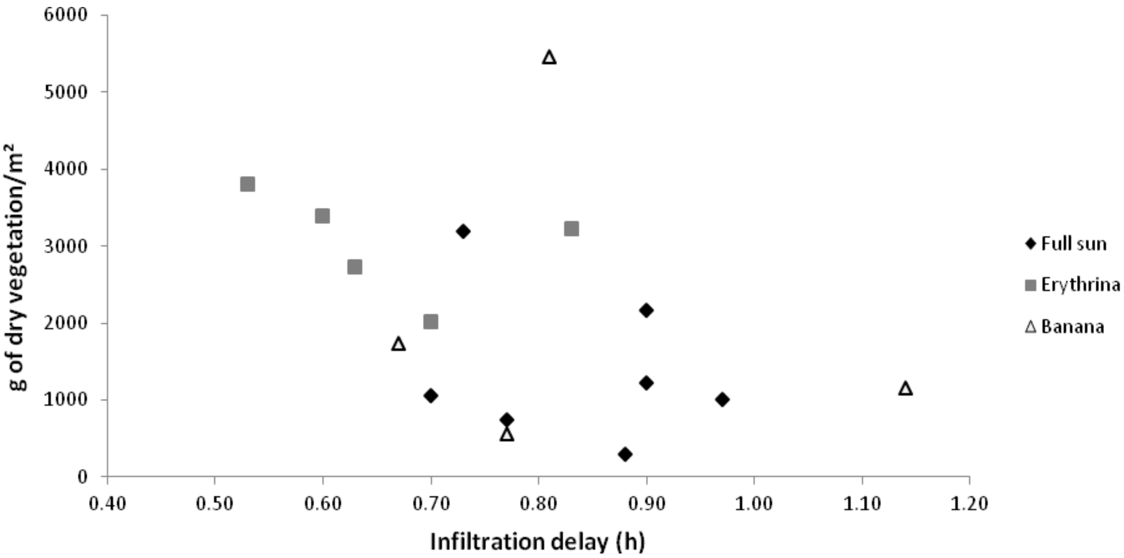



Figure 3.10 – relationship between infiltration delay and litter for different shade treatments across all sites

### *2.3.7 N FIXATION*

Figure 3.11 below shows the value of $\delta^{15}N$ in young and mature coffee leaves collected at sites 2 and 3 in 2011, progressively increasing with distance from the Erythrina tree. The values for young and mature Erythrina leaves were also included.

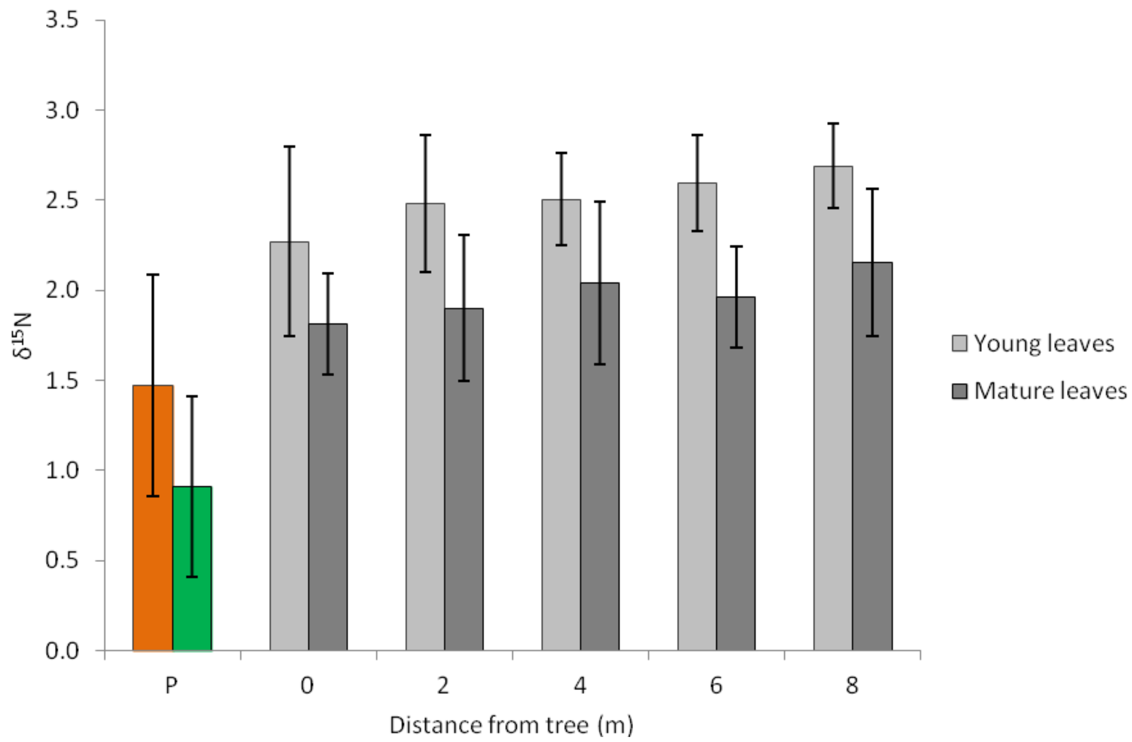



Figure 3.11 - δ15N values for coffee leaves and Erythrina leaves at various distance from an Erythrina tree; the coloured bars (at distance 'P') represent the Erythrina leaves, included in the graph for comparison. Orange = young leaves, green = mature leaves.

Table 3.12 below shows the outcomes of linear regressions on different subsets as well as all samples. In all subsets, there was a significant correlation between distance from the Erythrina tree and $\delta^{15}N$ with lower values for coffee plants closer to the tree. The $\delta^{15}N$ for all Erythrina leaves was significantly lower than that of the coffee leaves. A lower $\delta^{15}N$ in coffee leaves is a sign that a large portion of the nitrogen contained in the coffee leaves came from biologically fixed nitrogen in the soil (Boddey *et al.*, 2000). We therefore conclude that Erythrina trees in the sampled sites did fixed nitrogen, and that coffee plants absorb more of this additional source of N the closer they are to the tree.

Table 3.12 – summary of $\delta^{15}N$ values and linear regressions

| Subset | Mean $\delta^{15}N$ | StDev $\delta^{15}N$ | Pearson | Significance | R | $R^2$ | Adj. $R^2$ | Std. error of estimate |
|---|---|---|---|---|---|---|---|---|
| ALL | 2.164 | 0.419 | 0.41 | 0.002 | 0.41 | 0.168 | 0.151 | 0.386 |
| young leaves | 2.394 | 0.378 | 0.575 | 0.001 | 0.575 | 0.331 | 0.302 | 0.315 |
| mature leaves | 1.934 | 0.325 | 0.398 | 0.024 | 0.398 | 0.158 | 0.122 | 0.305 |
| site 2 | 2.195 | 0.443 | 0.426 | 0.009 | 0.426 | 0.181 | 0.152 | 0.408 |
| site 3 | 2.118 | 0.386 | 0.389 | 0.045 | 0.389 | 0.152 | 0.104 | 0.365 |

## 3.4 DISCUSSION

### *3.4.1 COFFEE YIELD*

Many factors affect coffee yield, including climate, management, and coffee phenological development. We were not able to detect any significant effect of shade on overall coffee yield. Pruning especially, is linked to yield, which is evident since removing large amount of coffee biomass (including buds in preparation for flowering) nine months before coffee is harvested, will have an effect on yield. Is it possible these results are mostly circumstantial – although farmers did indicate that coffee plants under full sun required more frequent pruning.

Furthermore, the shade levels studied were comparatively low (shade tree LAI rarely exceeding 1, both banana and Erythrina heavily pruned once or twice a year). Not finding any negative effects of shade at these levels is not entirely surprising, considering the given rates of optimal shade cover for coffee range between 20-65% (Beer, 1992).

Nevertheless, a study of the yield components did show significant differences in between shade treatments in terms of flowering and cherry growth. In 2010, plots under full sun treatment started out with signs of higher productivity at flowering time, yet by harvest this advantage had disappeared. Considering the highly unfavorable and sun-limited conditions of 2010 wet season (during which the cherries are developing) we emit the hypothesis that coffee plants in full sun attribute a higher ratio of resources than plants in shaded conditions, in bud production and flowering in March-May, and later in grain filling.  However, at the moment of allocating these resources, leaf development would be disadvantaged. Therefore, this strategy would pay off in years where sunlight is not limiting, such as in 2011 when plots in full sun had higher number of cherries, but not in 2010 when sunlight levels were lower. In other terms, the coffee plants under full sun show an inefficient use of resources, allotting too many limited resources to putting in place a production that they will not be able to sustain until harvest. On the other hand, the shaded plant, with more modest blossoming, make a wiser use of a resource, radiation, that proves limiting towards the end of the year. Unfortunately, our LAI measures were taken at the plot level; more detailed data on evolution of foliage and cherry biomasses on single plants or shoots would be necessary to properly test this hypothesis.

### *3.4.2 WATER AND N IN SOIL*

Clearer effects of shade were observed for water infiltration and litter. Observation of faster infiltration speeds in shaded plots, commonly associated with a less compacted soil structure, is consistent with the findings of Lin & Richards (2007). We emit the hypothesis that this could lead to decreased runoff, and decreased erosion, in shaded plots. A study currently underway on site 3 with field measurements of runoff and erosion will provide data to test this hypothesis.

Laboratory analysis of total N and C did not show any significant differences in between shade treatments. However, to find data that indicated biological fixation of nitrogen by Erythrina trees was surprising in this environment, considering the amount of fertilizer applied. Nygren & Ramirez (1995) described a rapid regeneration of Erythrina nodules after pruning. The time delay between tree pruning and the first application of fertilizer can be up to four months – it is possible that nodules might develop during this interval.

Unfortunately, these advantages tend to be underrated, as they are either not visible (infiltration) are overrun by excess fertilization. Is it likely they could improve the resilience of the system by sustaining productivity in times of lower fertilizer applications, due to low coffee prices (as in 2000-2003) or high fertilizer prices (likely in the near future).

### *3.4.3 PERSPECTIVES*

Sampling a larger amount of fields and over more than two years and sites might have been able to find some trends, if climate, position in the watershed, and management were accounted for. Using numerical models might offer an easier way of exploring these relationships, in situations where large amounts of field data over a long time span would be needed. Nevertheless, field measures allowed us to obtain a complete and representative view of on-site variables, e.g. ability to measure banana shade trees, soil litter, etc. Existing numerical models such as CAF2007 are limited in the amount of variables they can simulate (van Oijen *et al.*, 2010b)

Certain variables not considered in this study would have been valuable in helping to understand the effect of shade. Data on American leaf spot would have allowed to explore the effect of shade and humidity conditions on fungus incidence (Avelino *et al.*, 2005). Due to the heavy workload involved, N and erosion budgets were not measured; infiltration can only give a hypothetical idea of erosion, and measures of total N in the soil in no way accounts for the highly variable supply of mineral N. Studies in the Llano Bonito watershed are currently underway to better document these variables for 2013.

Considering we were working in an optimal area for coffee production with relatively low shade levels, it would be interesting to test the effect of allowing more tree growth by decreasing pruning, or increasing tree density.

# CHAPTER 4

# CALIBRATION OF A DYNAMIC MODEL OF A CROPPING SYSTEM

## 4.1 INTRODUCTION

### *4.1.1 PRESENTATION OF THE CAF2007 MODEL*

Process-based modeling can help us explore the impact of different factors (human or environmental) on cropping systems and the ecosystem services they provide, including crop production. In particular, designing coffee-based agroforestry systems can be challenging due to the presence of at least two perennial plant species that are interacting with each other over the span of several years. This creates a large amount of interactions and processes that must be taken into account on a several-year time scale. Changing climate and socioeconomic conditions in the developing countries where most coffee is grown has created a need for designing more sustainable agroforestry systems.

CAF2007 was developed specifically for the simulation of coffee-based agroforestry systems in Central America. CAF2007 is "*aimed at exploring the systems' response to strategic management decisions (fertilization 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)*" (van Oijen *et al.*, 2010b). The model functions at the plot scale over the full lifespan of a coffee plantation (generally 10-25 years). It was constructed based on the objective stated above as well as availability of data, described in a companion literature review of quantitative information of coffee agroforestry systems (van Oijen *et al.*, 2010a).

CAF2007 functions at the field scale but does account for spatial arrangements in the plot. It simulates field-level biomass of various plant organs and water, C and N stocks. The coffee field is divided into shaded and unshaded portions (see figure 4.1). The shaded portion of the field increases daily as the tree canopy grows, and suddenly decreases when trees are pruned. Each variable in the system is calculated separately; in the unshaded section, coffee plants are considered to function as a monoculture, while in the shaded part, both the shade trees and the coffee plants grow and interact with eachother. Plot-scale calculations are obtained by averaging the variables for each section based on the shaded area of the field.

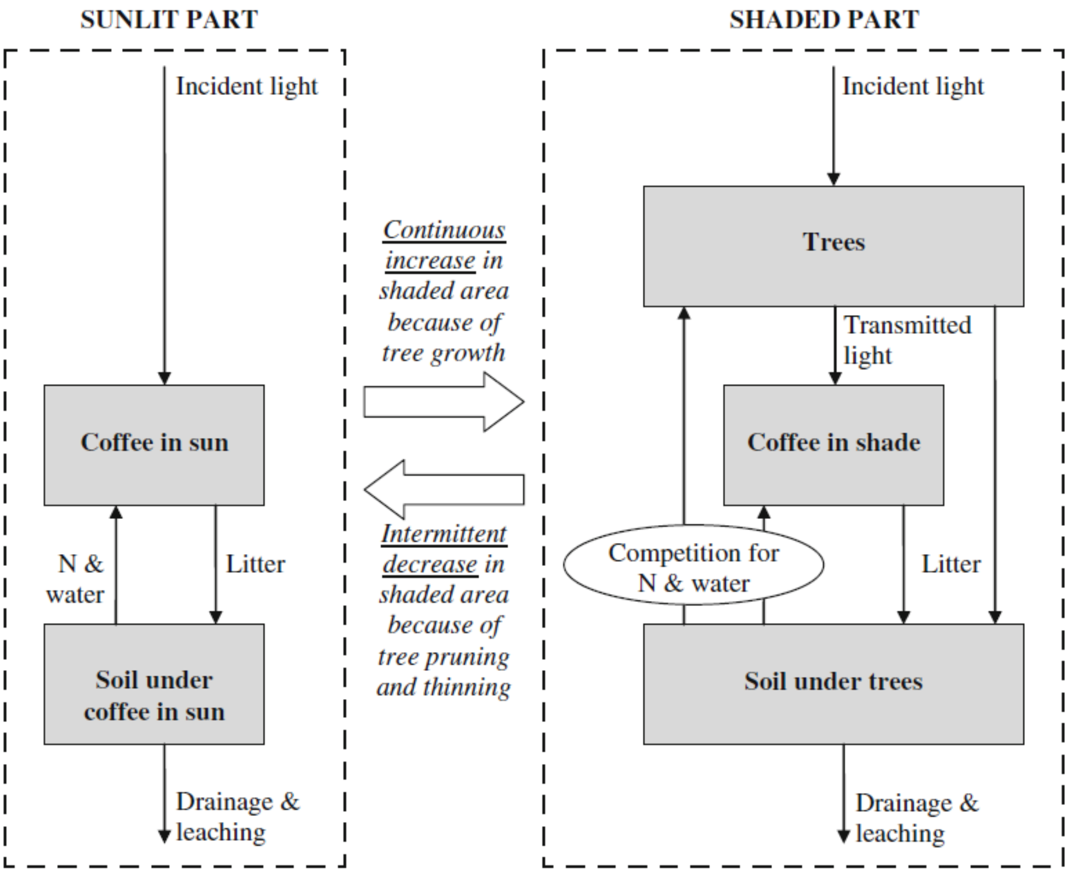



Figure 4.1 – basic function of the CAF2007 model, from van Oijen et al (2010b)

The model works with a daily time step and calculation of a number of state variables. A more detailed function can be found in van Oijen et al (2010b) and in the appendix of Remal (2009).

### 4.1.2 PARAMETER ESTIMATION

A fundamental part of ensuring model simulations are accurate is the adjustment of parameter values. Parameter values influence the importance of different processes in calculation of outputs.

CAF2007 relies on 112 parameters that influence the calculations of all the different compartments of the model. The model has been very incompletely validated so far (van Oijen *et al.*, 2010b), with parameter values relying on a review of scientific literature (van Oijen *et al.*, 2010a). Some parameters with no real-world equivalent are simply adjusted to a value which allows the model to function as expected. A first attempt at calibration by Remal (2009) was not concluded. We want to be able to use the model for comparing the effect of different management and climatic scenarios. The accuracy of parameter values must therefore be improved; where accurate data or direct measurements are available, we can directly inform them. Otherwise, they must be estimated. A sensitivity analysis can help prioritize which parameters need to be accurately estimated according to how much impact they have on model outputs (Saltelli, 2000).

CAF2007 contains many components (climate, management, plant physiology, soil processes, photosynthesis, etc) and many of these components interact. Estimating so many parameters which frequently interact with each other poses some complications; first and foremost due to the difficulty of testing out so many different combinations of parameter values in order to find the best one. A calibration of only a few parameters at a time is not very desirable in our case, since the optimal value for each parameter being dependent on others, and the effect of varying one parameter's value on the other's optimal value could be overlooked.

### *4.1.3 BAYESIAN CALIBRATION*

Two approaches are commonly used for parameter estimation: the frequentist and Bayesian approaches. Simple models with no more than two or three parameters can be estimated quite easily, for example using frequentist methods such as maximum likelihood or least squares method (Makowski *et al.*, 2006). These methods assume that parameters are fixed variables and do not take prior information on the parameters into account. However, these methods have difficulty dealing with large number of parameters; there are too many possible combinations of parameter values, which are often not independent.

Bayesian calibration makes use of output data as well as prior information on parameter values. This approach estimates parameter values simultaneously – a particularly useful feature for parameterization of complex models (Campbell *et al.*, 1999). In complex models, error reduction is more successful than other methods such as generalized least squares (Tremblay and Wallach, 2004). We have stated that CAF2007 has 112 parameters. Some, such as the STICS model, have over 200 (Brisson *et al.*, 1998). Bayesian methods also provide a coherent framework for dealing with uncertainty, by using the posterior probability distribution (Makowski *et al.*, 2006).

Baye's theorem states that $P(\theta|D) = p(D|\theta) \cdot p(\theta)$ where:

- $P(\theta|D)$ is known as the "posterior". This is the conditional probability distribution of θ taking data D into account. In other words, it shows the range of possible values for the parameters θ and the probability of each vector within that range. Because we are working with a large number of different parameters, $P(\theta|D)$ is shown as a matrix.
- $p(D|\theta)$ is the likelihood function. It shows us the probability distribution of the data $D$ for a set parameter vector $\theta$. This involves analysis of the model function itself.
- $p(\theta)$ is the "prior" – the probability distribution of parameters θ before we start using the data $D$ to refine it. The range and form of the probability function is dependent on information encountered from field data or scientific literature.

Bayesian methods imply a certain form of subjectivity since we must define a prior probability distribution for the parameters. In the Bayesian approach, parameters are defined as random variables and the prior and posterior parameter distributions represent our belief about parameter values before and after data observation (Van Oijen, 2008). Care must be taken in the definition of prior probability distributions; where accurate data is lacking, setting excessively large ranges in compensation can cause the calibration to be less efficient. This is a problem especially for parameters which do not have any biological or physical meaning. Even when relying on scientific data, sources of information may be heterogeneous and must be carefully evaluated for their accuracy (Metselaar, 1999).

### *4.1.4 MARKOV CHAIN MONTE CARLO ALGORITHMS*

Bayesian calibration can be done in several ways. Monte Carlo methods are an increasingly popular application of Bayesian calibration (Malakoff, 1999). The method generates a random sample of parameter values, which allows us to derive an approximation of the posterior distribution. The Metropolis-Hastings algorithm is an iterative Markov chain Monte Carlo algorithm (MCMC) that randomly generates a sample of parameter values from the posterior parameter distribution (Geyer, 1992). The iterative aspect of the algorithm allows it to "walk through parameter space" while testing different combinations of parameter values – known as a parameter vector (Van Oijen, 2008). The algorithm starts with an initial parameter vector $\theta_0$. At each iteration, a "candidate" parameter vector is generated within parameter space with n dimensions (n being the number of parameters). This candidate is generated by taking a "step" away from the current vector, the width of which depends on the uncertainty of each parameter.

The probability that the candidate vector leads to a model fit of the measured data is calculated using the Metropolis ratio.

If the probability is more than 50% the candidate parameter vector is accepted. Although the choice of parameter vectors at each iteration is initially random, after a few thousand iterations and exploration of the parameter space, areas of "higher probability" begin to be defined and new parameter vectors are more likely to be located there. If an area of higher probability does emerge, sampling will therefore progressively focus in that space. The range of values, or the mean value, of the parameters in this area can then be used to update the parameter values of the model with the knowledge that these values are the optimal combination that allow the model to simulate the observed data (Van Oijen, 2008).

In this chapter, we therefore aim to use **Bayesian and MCMC calibration** techniques to adjust the parameter values of a **dynamic agroforestry model** (CAF2007) in order to make the **simulated outputs match the measured variables** in a defined production area for a) **value ranges** and b) **response to climate and management parameters**.

## 4.2 METHODOLOGY

### *4.2.1 PARAMETER SELECTION*

All the parameters of the model were listed and categorized according to how they could be informed. The categories of parameters were:

- parameters whose value could be directly measured or known e.g. those relating to local geography or management, or that were well documented in scientific literature or field experiments
- parameters that did not have enough impact on model output according to a sensitivity analysis, and therefore did not need to be calibrated
- parameters with significant impact on model outputs that could not otherwise be documented, and therefore needed to be calibrated

The parameters that could not be directly informed were subject to a sensitivity analysis in order to determine their effect on model outputs. The analysis performed by Remal (2009) was used, which varied parameter values within a range defined in van Oijen *et al* (2010a) to determine the parameters that most influenced seven output variables shown in table 4.1. Coefficients of variation were then calculated for each parameter. Those parameters with a coefficient of variation above a given threshold were included in the list of parameters for calibration.

Table 4.1 – list of main model outputs

| Output | Unit |
|---|---|
| Average coffee productivity | ton DM/ha/yr |
| Average wood productivity | $m^3$/ha/yr |
| Average N-emission | kg of N/ha/yr |
| Average N-leaching | kg of N/ha/yr |
| Average C-sequestration on-site | t of C/ha/yr |
| Average C-soil runoff | t of C/ha/yr |
| Average water drainage | mm/day |

The script used by Remal (2009) can be found in annex II.

### *4.2.2 FIELD DATA USED FOR CALIBRATION*

In order to adjust the values of parameters selected using Bayesian technique, a certain number of field measurements corresponding to model outputs were chosen. All model components had to be represented (coffee, tree and soil). Additionally, the model simulates shaded and sunny parts of the coffee field separately. In order to have accurate data we sampled plots of 10-20 plants under distinct shade treatments within a field (e.g. within a coffee field with Erythrina trees, select plots of plants directly under the tree and other plots in between trees in full sun). A full description of the sites chosen and plots description can be found in Chapter 2.

In each site, measures of coffee and tree Leaf Area Index, coffee wood biomass, and coffee yield were performed. Additionally, a weather station was installed at sites 1 and 3. Weather data for site 2 was interpolated from the data of site 3 and 4 (another study site not used in this chapter), with a 1.5°C colder temperature due to site 3 having a higher altitude. Table 4.2 summarizes the data used.

Table 4.2 – Unit, sampling frequency, location and scale of the variables measured on the field for model calibration

| Type | Variable | Unit | Frequency | Sites measured | Sampled scale |
|---|---|---|---|---|---|
| Climate | Precipitation | mm | 30min | 1, 3 and 4 | Site |
| | Photosynthetically Active Radiation (PAR) | ?? | | | |
| | Relative humidity | % | | | |
| | Wind speed | m/s | | | |
| | Temperature | °C | | | |
| Soil | Volumetric Water content | % | 30min | 1, 3 and 4 | 15, 30, 60, 100, 150cm depth in every plot |
| Coffee | Woody biomass | $cm^3$ | 3 months | All | Plant (sum of shoots and stems) |
| | Leaf Area Index (LAI) | $m^2/m^2$ | 3 months in 2010; monthly afterwards | All | Plot |
| | Yield (calculated from yield components – see Ch.2) | tons of coffee cherries/ha | Yearly in October | All | Plot (subsample of plants and shoots) |
| Tree | LAI | $m^2/m^2$ | 3 months in 2010; monthly afterwards | All | Plot |

The modalities for data collection and main results are presented in Chapter 2. Furthermore, tables of raw data are available in annex III. Table 4.3 shows the range of values measured for each variable in different fields (except for climate data).

Climate and management data are also the ones presented in Chapter 2. Daily maximum and minimum temperature measurements were used to calculate vapor pressure (VP). All dates were converted into numbered days of the year, following the format used in CAF2007.

Data was collected on leaf and branch biomass for Erythrina trees. In march 2011, all branches and leaves were removed from five Erythrina trees in site 1. Branches and leaves were separated, dried for 48 hours at 65°c and weighed for each tree. The weight was divided by two for a rough estimate of CB0T and CL0T parameters (carbon in tree branches and leaves respectively).

### *4.2.3 PROGRAMMING BAYESIAN CALIBRATION AND MCMC*

Script files were programmed in MATLAB for running calibration of CAF2007 – a reference of all the scripts mentioned in this section can be found in Annex II. First of all, weather data files and management parameters were set for each of the three sites that would be calibrated. Site 2 did not have any weather stations so the data from site 3 was used. The management parameters were set based on the information presented in chapter 2. This information was put together in the *setsite1.m*, *setsite2.m*, and *setsite3.m* files.

The model was then initialized using the *initialise_caf2007_LB.m* file, which contained default management parameter values for Llano Bonito (average of all sites) as well as updated parameter values for those that could be informed using available data or reliable sources from scientific literature. Additional outputs (mostly state variables) were also added in order to track model behavior during the calibration process.

The *fLogPriorBeta.m* file coded in the α and β values of the Beta distribution from the *Pstruct* function, which obtained the α and β from the mean, minimum and maximum parameter values in *pS_LB_coffee.m*, *pS_LB_soil.m* and *pS_LB_tree.m* files. These values were taken from the literature review of scientific information on coffee production of van Oijen et al (2010a).

The last required element was the list of data to be used for calibration, with one dataset for each site (*data_LBcalib1.m*, *data_LBcalib2.m* and *data_LBcalib3.m*). Each data point was associated to a specific date (number of cumulated days in the simulation) and standard deviation. The same amount of every variable was used across all sites in order to avoid biasing the calibration by giving more weight to a frequently measured variable. Variables with a high number of measures (e.g. soil water content) were reduced to monthly or bimonthly values.

The calibration ran using a Metropolis-Hastings MCMC-type algorithm shown in *MCMC_script_CAF_MULTISITE.m* and *MCMC1cl_MULTISITE.m*. The calibration ran for 25,000 iterations.

The values for each parameter for each iteration were recorded in an Excel file. The evolution of each parameter was graphed in order to detect reductions in parameter range or stabilization around a mean value. Parameters with significant and long-lasting reduction in the range of their values saw their minimum and maximum values adjusted accordingly. This criterion was conditional on the iterations having fully explored parameter space. If the maximum and minimum values were changed from the original, the mean between the new max and min would replace the default value. Range reductions were only considered if they were stable, i.e. lasted for more than 15,000 iterations.

### 4.2.4 EVALUATING SUCCESS OF CALIBRATION

In order to measure whether changing the parameter values improved the accuracy of the model simulations compared to the measured data, the Root Mean Squared Error (RMSE) was calculated for different output variables.

## 4.3 RESULTS

### 4.3.1 INFORMING PARAMETERS WITH DATA/LITERATURE

Table 4.4 below shows the list of parameters whose values were directly adjusted using scientific literature, field data, or local information from technicians or farmers. In the case of information from scientific literature or technicians, the source was included as a reference. Variables relating to the management of each plot were filled in later, before starting each simulation.

Table 4.4 – list of parameters that were considered sufficiently well informed not to be included in the calibration

| Parameter | Name | Unit | Value | Source | Details |
|---|---|---|---|---|---|
| Altitude | ALT | m | 1171 | Data | see Ch. 3 |
| Initial C biomass in branches | CB0T | kg C $m^{-2}$ | 0.1 | Data | see Ch. 4 |
| Bean carbon concentration | CCONC | kg C kg-1 DM | 0.44 | Data | see Ch. 3 |
| Initial biomass leaves | CL0 | kg C $m^{-2}$ | 0.05 | Data | see Ch. 3 |
| Initial C biomass in leaves | CL0T | kg C $m^{-2}$ | 0.05 | Data | see Ch. 4 |
| Initial amount of litter | CLITT0 | kg C $m^{-2}$ | 0.33 | Data | see Ch. 3 |
| Initial C/N ratio in litter | CNLITT0 | kg C kg-1 N | 17 | Data | see Ch. 4 |
| Default atmospheric CO2 concentration | CO20 | ppm | 350 | Scientific literature | IPCC (2011) |
| CO2 concentration of the atmosphere | CO2A | ppm | 380 | Scientific literature | IPCC (2011) |
| Initial biomass storage organs | CP0 | kg C $m^{-2}$ | 0 | Data | see Ch. 3 |
| Initial biomass roots | CR0 | kg C $m^{-2}$ | 0.05 | Scientific literature | Defrenet (2012) |
| Initial C biomass in roots | CR0T | kg C $m^{-2}$ | 0.2 | Scientific literature | Defrenet (2012) |
| Initial C biomass in stems | CS0T | kg C $m^{-2}$ | 0.1 | Scientific literature | |
| Initial biomass stems plus branches | CW0 | kg C $m^{-2}$ | 0.05 | Data | see Ch. 3 |
| Pruning coffee: first time | DAYPRUNC0 | d | 1825 | Management | - |
| Pruning coffee: interval | DAYPRUNCI | d | 1825 | Management | - |
| Pruning trees: first time | DAYPRUNT0 | d | 182 | Management | - |
| Pruning trees: interval | DAYPRUNTI | d | 365 | Management | - |
| Thinning trees: first and second times | DAYTHINT | d | [-1,1000] | Management | - |
| First day of fertilization | DOYFERT(1 | d | 15 | Management | - |
| Second day of fertilization | DOYFERT(2 | d | 136 | Management | - |
| Third day of fertilization | DOYFERT(3 | d | 228 | Management | - |
| Initial development stage | DVS0 | - | 0 | Management | - |

| | | | | | |
|---|---|---|---|---|---|
| N/C ratio leaves (minimum) | FNCLMINT | kg N $kg^{-1}$ C | 0.68 | Scientific literature | |
| Pruning coffee: fraction removed | FRPRUNC | kg $kg^{-1}$ | 0.95 | Management | - |
| Pruning trees: fraction removed | FRPRUNT | kg $kg^{-1}$ | 0.5 | Management | - |
| Thinning trees: fraction removed | FRTHINT | # $\#^{-1}$ | 0.5 | Management | - |
| Lower bound of the range of SLA expressed as the fraction of the maximum | FSLAMIN | - | 0.45 | Data | See Ch. 3 |
| Fraction of water content at air dryness | FWCAD | - | 0.01 | Data | see Ch. 3 |
| Fraction of water content at field capacity | FWCFC | - | 0.65 | Data | see Ch. 3 |
| Fraction of water content at water saturation | FWCWET | - | 0.87 | Data | see Ch. 3 |
| Fraction of water content at wilting point | FWCWP | - | 0.41 | Data | see Ch. 3 |
| Maximum LAI | LAIMAXT | $m^2$ $m^{-2}$ | 5.6 | Data | see Ch. 3 |
| Latitude | LAT | ºN | 9.92 | Data | see Ch. 3 |
| Fertilization rate | NFERT | kg N ha-1 | [100,100, 100] | Management | - |
| Minimum of daily rain that triggers flowering after the start of the new year | RAINHI | mm d-1 | 12 | Data | see Ch. 3 |
| Rooting depth | ROOTD | m | 1 | Data | see Ch. 3 |
| Maximum specific leaf area | SLAMAX | m2 kg-1 C | 2.4 | Data | Taugourdeau (2010) |
| Specific Leaf Area | SLAT | $m^2$ $kg^{-1}$ C | 32 | Scientific literature | see Annex III |
| Slope | SLOPE | % | 5 | Data | see Ch. 1 |
| Time constant for litter decomposition | TCLITT | d | 500 | Data | Charbonnier, 2011 |
| Initial tree density | TREEDENS0 | # $m^{-2}$ | 0.025 | Management | - |
| Water content at saturation | WCST | $m^3$ $m^{-3}$ | 0.63 | Data | see Ch. 3 |

### *4.3.2 PRIORITIZING PARAMETERS FOR CALIBRATION*

Table 4.5 shows the results of the sensitivity analysis from Remal (2009) and the parameters selected for calibration. The threshold was set at a minimum value of 0.10 in order for the parameter to be taken into account in the calibration. Based on that threshold, a total of 36 parameters were selected for calibration. These parameters are presented later on in the table of calibration outputs.

Table 4.5 – outcomes of sensitivity analysis, showing the list of parameters with the coefficient of variation

| Parameter | Identifier | Unit | Sensitivity |
|---|---|---|---|
| Biotic growth factor | BETA | - | 0.02 |
| Initial C/N ratio in unstable organic matter | CNSOMF0 | kg C kg-1 N | 0.10 |
| Initial C/N ratio in stable organic matter | CNSOMS0 | kg C kg-1 N | 0.11 |
| Initial concentration of organic matter | CSOM0 | kg C m-2 | 0.00 |
| Time between start and full productivity | DAYSPLNOP | d | 0.13 |
| Time between pruning and full productivity | DAYSPRNOP | d | 0.11 |
| Phenological stage activating competition for C allocation | DVSSINKL | - | 0.10 |
| C Allocation to branches | FB | kg C kg$^{-1}$ | 0.21 |
| Initial fraction of the soil organic matter which is unstable | FCSOMF0 | - | 0.00 |
| Efficiency of litter transformation | FLITTSOMF | kg kg$^{-1}$ | 0.13 |
| C Maximum Allocation to leaves | FLMAX | kg C kg$^{-1}$ | 0.04 |
| Lower bound of the range of N/C ratio leaves expressed as the fraction of the maximum | FNCLMIN | - | 0.10 |
| C Allocation to stems | FS | kg C kg$^{-1}$ | 0.23 |
| Efficiency of organic matter transformation | FSOMFSOMS | kg kg$^{-1}$ | 0.14 |
| Lower bound of range of leaves lifespan expressed as the ratio of maximum | FTCCLMIN | - | 0.15 |
| Fraction of minimum life time of C in leaves | FTCCLMINT | - | 0.14 |
| Respiration/photosynthesis ratio | GAMMA | kg kg$^{-1}$ | 0.19 |
| Multiplier for radiation | I0MULT | - | 0.01 |
| Allometric constant linking C biomass in branches to crown area | KCA | m$^2$ | 0.13 |
| Allometric constant linking C biomass in branches to crown area | KCAEXP | - | 0.00 |
| Light extinction coefficient | KEXT | m$^2$ m$^{-2}$ | 0.11 |
| Light extinction coefficient | KEXTT | m$^2$ m$^{-2}$ | 0.00 |
| Allometric constant linking C biomass in stem to height | KH | m | 0.24 |
| Allometric constant linking C biomass in stem to height | KHEXP | - | 0.13 |
| N-emission rate constant from soil at field capacity | KNEMIT | kg N kg$^{-1}$ N d$^{-1}$ | 0.15 |
| N-fixation capacity | KNFIX | kg N kg$^{-1}$ C | 0.12 |
| Km for N-uptake | KNMIN | kg N m$^{-2}$ | 0.49 |
| N-uptake: Minimum N uptake capacity | KNMINT | kg N m$^{-2}$ | 0.13 |
| Vmax for N-uptake | KNUPT | kg N m$^{-2}$ d$^{-1}$ | 0.52 |
| N-uptake: N-uptake rate | KNUPTT | kg N m$^{-2}$ d$^{-1}$ | 0.00 |
| Rain interception capacity | KRNINTC | mm (m$^2$ m$^{-2}$)$^{-1}$ | 0.12 |
| Rain interception capacity | KRNINTCT | mm (m$^2$ m$^{-2}$)$^{-1}$ | 0.00 |
| Run-off constant, protection by LAI | KRUNOFF | m2 m-2 | 0.06 |
| Parameter for calculation of storage organs sink strength | KSINKPLAI | m2 m-2 | 0.04 |

| | | | |
|---|---|---|---|
| Parameter for calculation of storage organs sink strength | KSINKPPAR | m2 d MJ-1 | 0.08 |
| Light use efficiency | LUET | kg C $MJ^{-1}$ PAR | 0.05 |
| N/C ratio leaves (maximum | NCLMAX | kg N kg-1 C | 0.05 |
| N/C ratio storage organs | NCP | kg N kg-1 C | 0.08 |
| N/C ratio roots | NCR | kg N kg-1 C | 0.18 |
| N/C ratio stems and branches | NCW | kg N kg-1 C | 0.09 |
| Multiplier for external N-inputs | NFERTMULT | - | 0.03 |
| Initial values NMIN | NMIN0 | kg N $m^{-2}$ | 0.00 |
| Multiplier for rain | RAINMULT | - | 0.00 |
| Ratio of NMIN in drainage to bulk soil | RNLEACH | kg N kg-1 N | 0.19 |
| Ratio of runoff in bulk soil | RRUNBULK | kg kg-1 | 0.00 |
| Rubisco content | RUBISC | g $m^{-2}$ | 0.13 |
| Shade projection | SHADEPROJ | $m^2$ $m^{-2}$ | 0.03 |
| Sink strength for leaves | SINKL | - | 0.16 |
| Sink strength for storage organs | SINKPMAX | - | 0.20 |
| Sink strength for roots | SINKR | - | 0.17 |
| Sink strength for stems plus branches | SINKW | - | 0.19 |
| Life time of C in branches | TCCBT | d | 0.02 |
| Maximum lifespan of leaves | TCCLMAX | d | 0.15 |
| Maximum life time of C in leaves | TCCLMAXT | d | 0.00 |
| Average lifespan of roots | TCCR | d | 0.14 |
| Life time of C in roots | TCCRT | d | 0.01 |
| Time constant for unstable organic matter decomposition | TCSOMF | d | 0.65 |
| Time constant for stable organic matter decomposition | TCSOMS | d | 0.00 |
| Base temperature for maturation | TMATB | °C | 0.10 |
| Thermal time to maturation | TMATT | °C | 0.11 |
| Optimum temperature for C assimilation | TOPTT | ºC | 0.00 |
| Addition-constant for temperature | TPLUS | ºC | 0.05 |
| Transpiration coefficient | TRANCO | mm d-1 | 0.10 |
| Transpiration coefficient | TRANCOT | - | 0.00 |
| Total temperature | TTOLT | ºC | 0.00 |
| Growth efficiency | YG | kg C $kg^{-1}$ C | 0.14 |

### *4.3.3 CALIBRATION OUTCOMES*

The MCMC algorithm was run for 50,000 iterations, of which the first 5000 were discarded. The iteration chain for each parameter was then plotted in order to look for signs of the iterations stabilising around a certain value, or at least within a reduced range. Apparent "stabilisations" of parameter values were only taken into account if occurred after fully exploring the entire parameter space, if they lasted at least 15,000 iterations, and lasted till the end of the calibration. In those cases, a new value was given to the parameter: either the value it stabilised at, or a mean value within its new, more reduced range.

Table 4.6 summarizes the outcomes of the calibration for each parameter and the changes that were made to parameter values. The majority of parameters saw at some reduction in their range, except for RUBISC which did not show any sign of reducing its original range. In the case of stabilisation of the parameter maximum and minimum values for at least 15,000 iterations, the mean of the stable segment was calculated and used as the new parameter value.

If the calibration simply resulted in a reduction of the parameter maximum and minimum values, the new value was calculated as the mean between the new maximum and new minimum.

Table 4.6 – minimum and maximum values of parameter ranges before and after calibration, showing the mean (value given to parameter before calibration) and the new value given after calibration

| | **Before calibration** | | | **After calibration** | | |
|---|---|---|---|---|---|---|
| **Parameter name** | Min | Max | Mean | Min | Max | New value |
| CNSOMF0 | 5 | 20 | 12 | 10 | 20 | 15 |
| CNSOMS0 | 5 | 20 | 11 | 12 | 16 | 14 |
| DAYSPLNOP | 760 | 1600 | 900 | 900 | 1300 | 1100 |
| DAYSPRNOP | 0 | 730 | 365 | 100 | 700 | 400 |
| DVSSINKL | 0 | 1 | 0.4 | 0.1 | 0.7 | 0.4 |
| FB | 0.2 | 0.3 | 0.23 | 0.22 | 0.26 | 0.235 |
| FLITTSOMF | 0.4 | 0.9 | 0.75 | 0.65 | 0.9 | 0.077 |
| FNCLMIN | 0.6 | 0.9 | 0.64 | 0.6 | 0.67 | 0.62 |
| FS | 0.1 | 0.5 | 0.28 | 0.2 | 0.4 | 0.29 |
| FSOMFSOMS | 0 | 0.3 | 0.03 | 0.04 | 0.1 | 0.07 |
| FTCCLMIN | 0.5 | 0.8 | 0.64 | 0.55 | 0.75 | 0.65 |
| FTCCLMINT | 0.05 | 0.5 | 0.1 | 0.05 | 0.08 | 0.065 |
| GAMMA | 0.2 | 0.6 | 0.55 | 0.3 | 0.5 | 0.4 |
| KCA | 1 | 25 | 17 | 5 | 15 | 10 |
| KEXT | 0.3 | 1.1 | 0.76 | 0.3 | 0.45 | 0.375 |
| KH | 1 | 10 | 5.1 | 3 | 8 | 5 |
| KHEXP | 0.1 | 1 | 0.31 | 0.01 | 0.05 | 0.25 |
| KNEMIT | 0.00006 | 0.006 | 0.0006 | 0.0003 | 0.001 | 0.0007 |
| KNFIX | 0.01 | 0.03 | 0.019 | 0.02 | 0.03 | 0.025 |
| KNMIN | 0.0036 | 0.36 | 0.036 | 0.0036 | 0.012 | 0.078 |
| KNMINT | 0.00082 | 0.082 | 0.0082 | 0.00082 | 0.001 | 0.00095 |
| KNUPT | 0.0002 | 0.02 | 0.002 | 0.003 | 0.008 | 0.005 |
| KRNINTC | 0.1 | 1 | 0.25 | 0.1 | 0.25 | 0.175 |
| NCR | 0.02 | 0.1 | 0.045 | 0.02 | 0.045 | 0.035 |
| RAINHI | 5 | 20 | 10 | 6 | 12 | 9 |
| RNLEACH | 0.5 | 1.5 | 1 | 1 | 1.4 | 1.2 |
| RUBISC | 0.5 | 5 | 0.54 | - | - | 0.5 |
| SINKL | 0.5 | 2.5 | 1.2 | 0.06 | 0.09 | 0.075 |
| SINKPMAX | 1.5 | 7.5 | 3.6 | 1.5 | 4 | 2.5 |
| SINKR | 1 | 5 | 2.5 | 1 | 1.5 | 1.25 |
| SINKW | 1 | 5 | 2.1 | 4 | 5 | 4.5 |
| TCCLMAX | 500 | 1300 | 650 | 700 | 1100 | 900 |
| TCCR | 1000 | 4000 | 2000 | 1500 | 3500 | 2500 |
| TCSOMF | 3750 | 15000 | 7500 | 6000 | 12000 | 9000 |
| TMATB | 5 | 15 | 10 | 5.5 | 9 | 7.2 |
| TMATT | 2300 | 3300 | 2780 | 2400 | 3000 | 2700 |
| TRANCO | 2 | 10 | 7.1 | 8 | 10 | 9 |
| YG | 0.6 | 0.8 | 0.74 | 0.76 | 0.8 | 0.78 |

### 4.3.4 EVALUATION OF THE CALIBRATION PROCESS

Table 4.7 shows the Root Mean Squared Error (RMSE) for the output variables that were used to calibrate the model. 'Initial simulation' shows model performance with the original parameter values in the model default version; 'after calibration' shows the RMSE after parameter values have been changed according to the optimal values found during calibration.

Table 4.7 – RMSE values for output variables used in model calibration

| Variable | | Site 1 | Site 2 | Site 3 |
|---|---|---|---|---|
| Yield | Initial simulation | 2.36 | 1.95 | 3.47 |
| | After calibration | 1.08 | 1.22 | 1.68 |
| Coffee LAI | Initial simulation | 1.69 | 2.01 | 1.2 |
| | After calibration | 0.52 | 0.88 | 0.67 |
| Tree LAI | Initial simulation | 1.22 | 1.48 | 1.63 |
| | After calibration | 0.89 | 0.70 | 0.45 |
| Coffee wood biomass | Initial simulation | 2.30 | 2.01 | 1.87 |
| | After calibration | 0.34 | 0.46 | 0.33 |
| Soil water content | Initial simulation | 0.22 | - | 0.14 |
| | After calibration | 0.06 | - | 0.04 |

Wood biomass and LAI measured on the field had higher growth rates as well as stronger decreases in value during pruning. For LAI, the calibrated model showed an increase of LAI values closer to the measured data, thus improving the RMSE. However, measured LAI remained much more variable than simulated LAI. This is mainly due to a high decrease in measured LAI around December every year, attributed not only to climatic and phonological factors, but to defoliation of coffee by coffee pickers during harvest (although the importance of this effect is not known, it is a widely recognized phenomenon by the farmers).

Similarly, the increase of RMSE for coffee wood biomass was mainly caused by an increase of simulated wood biomass values post-calibration, bringing them within the range of measured values.

### 3.3.5 EVALUATION OF SIMULATION CAPABILITIES OF THE CALIBRATED MODEL

In chapter 1 we showed a strong relationship between fertilization and yield based on data from interviews with farmers (figure 4.2, copied from chapter 1). Using that data, the 32 plots were replicated in model and a similar relationship between applied nitrogen and yield was observed – see figure 4.3. The climate data used for each simulation was taken from the nearest weather station; and the management practices were updated for each simulation according to the information given by farmers (amount, frequency and dates of fertilizer applied, shade tree and coffee plant density, and dates and intensity of pruning of coffee and shade trees). Other species of Erythrina shade trees were considered to be equivalent to *E. poeppigiana*. Other shade trees (e.g. banana, avocados, fruit trees) were included in the simulation, by halving their density and adding them to any Erythrina trees already present.

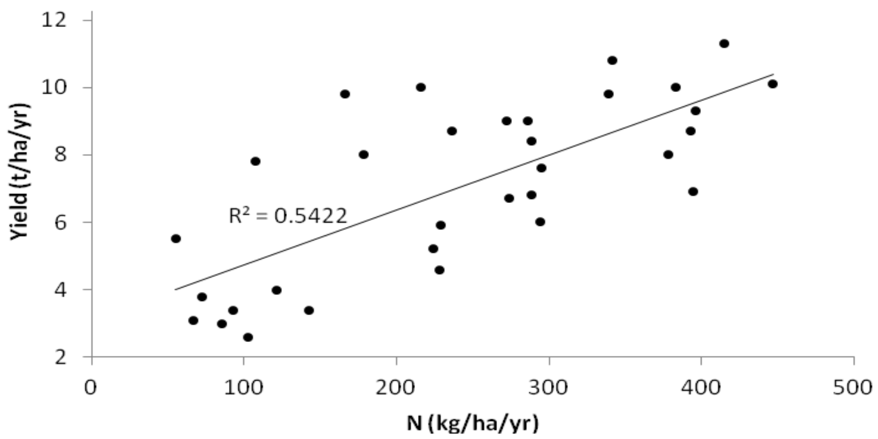



Figure 4.2 – relationship between applied nitrogen and declared yield for the plots in chapter 1

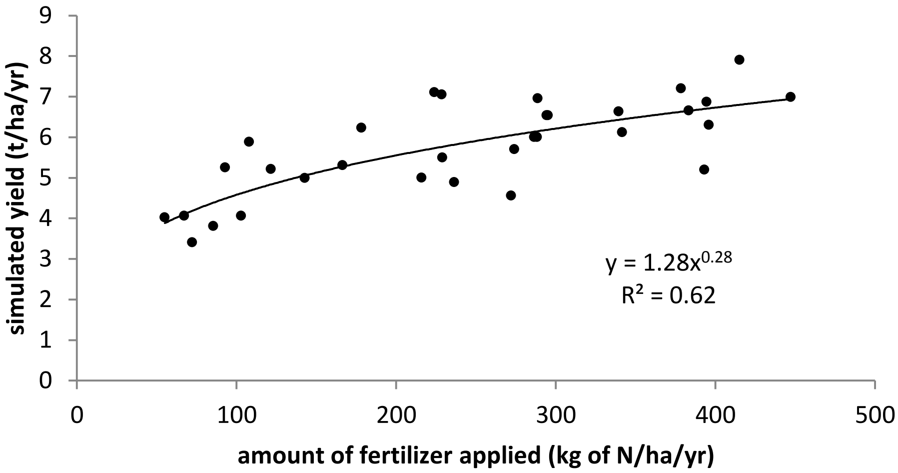
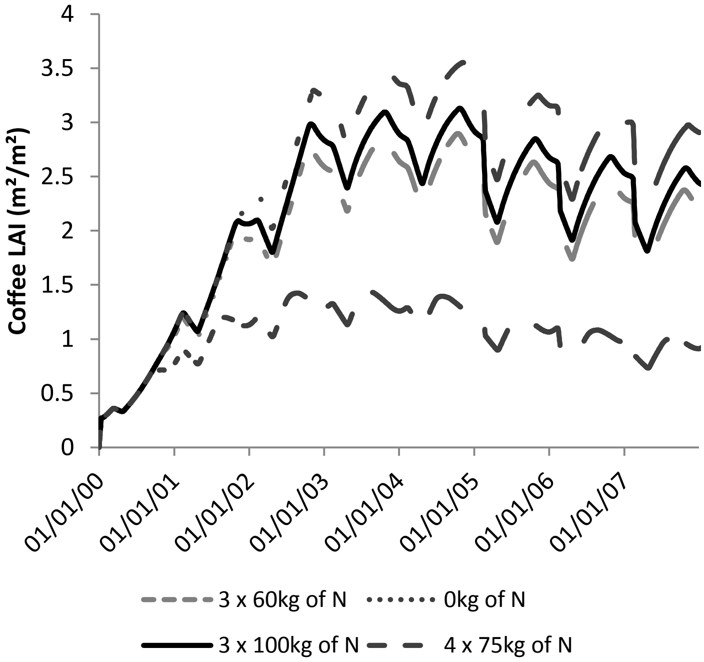
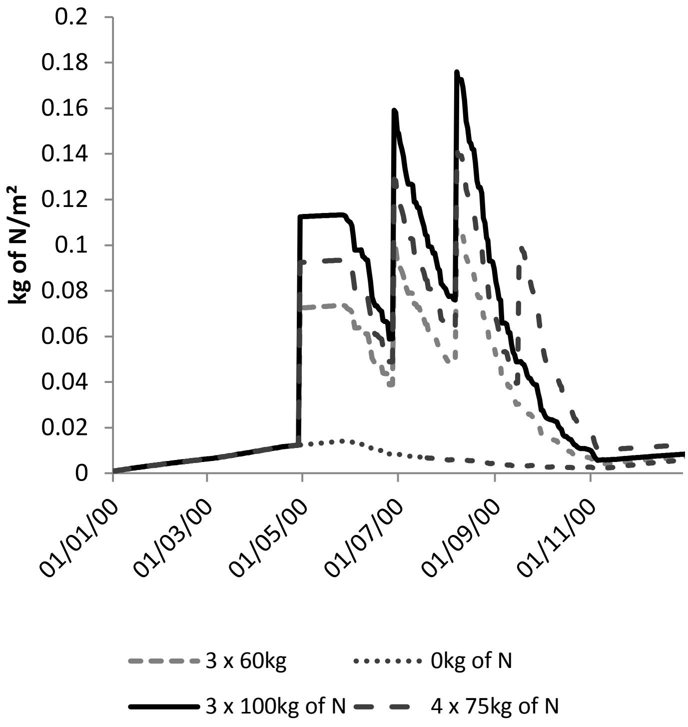



Figure 4.3 – simulated yields with management and climate parameters inputted from the plots in chapter 1

A variety of simulations were performed in order to test how the model simulated the output variables under different parameter values.



Coffee LAI (m²/m²)
4
3.5
3
2.5
2
1.5
1
0.5
0
01/01/00
01/01/01
01/01/02
01/01/03
01/01/04
01/01/05
01/01/06
01/01/07
3 x 60kg of N
0kg of N
3 x 100kg of N
4 x 75kg of N

kg of N/m²
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
01/01/00
01/03/00
01/05/00
01/07/00
01/09/00
01/11/00
3 x 60kg
0kg of N
3 x 100kg of N
4 x 75kg of N

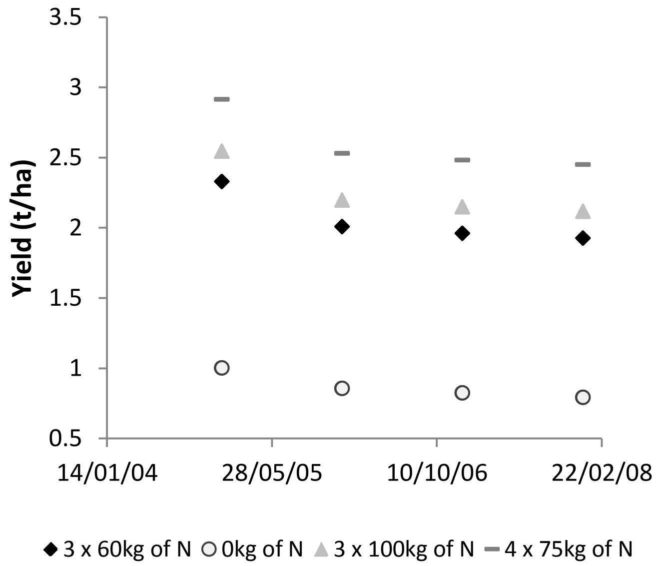



Figure 4.5 – comparison of different simulation scenarios; showing from top to bottom: a) effect of fertilisation on coffee LAI, b) effect of fertilisation on N leaching over one year; and c) effect of fertilization on yield

## 4.4 DISCUSSION

### *4.4.1 EFFECTIVENESS OF CALIBRATION*

Has the calibration worked?, e.g. can the model be brought to accurately simulate measured data, and more importantly, do the simulations accurately reflect plant growth and changes in the system over time, and are they sensitive to changes in management and climate.

Precision of model simulations after calibration

Significant reductions in RMSE values were achieved after model calibration, ensuring that the average values of output variables was consistent with data measured on the field. In terms of plant biomass, the model tended to have smaller ranges of annual variability than field measures. The higher variability of field measures may be exacerbated by exterior factors, such as human interventions and pests and diseases, causing strong decreases in plant biomass that the model cannot replicate. Instead, the model seemed more sensitive to the lower levels of sunlight during the wet season which caused a decrease in growth rate and even a decrease in overall LAI as leaf senescence began to outpace growth. Overall these differences did not prevent the model from simulating average biomass values that were reasonably close to the average field measures. However, this may be a indication that parameter selection could be improved, and the sensitivity analysis extended to a wider variety of outputs, in order to perform a higher quality selection of the most important parameters for calibration – as suggested by Wallach *et al* (2001).

Applications

The calibration presented was clearly intended to make CAF2007 functional for use within the Llano Bonito valley. The use of two different weather stations allowed the calibration to be done of different weather patterns representing the watershed – in particular, differences in levels of sunlight and humidity. Due to Costa Rica's highly variable topography and climate, applying to model to other areas would require a separate calibration.

A larger-scale application of CAF2007 is planned under the CAFADAPT project, which will involve data collection across several Central American countries for calibration of the model for the whole region (FONTAGRO, 2011).

Time constraints prevented us from taking a further step in the model programming which would have been to use the posterior probability distributions of parameters to take into account uncertainty – a useful advantage that comes with the use of Bayesian techniques. For each given simulation, around 500-1000 combinations of the most likely parameter values could be simulated and produce probability distributions of the model outputs.

### *4.4.2 LIMITATIONS OF BAYESIAN TECHNIQUE*

Improving parameter selection

Reducing the number of parameters in the calibration process could have also led to reduced error of the model. Ongoing investigations on coffee agroforestry systems in Central America, in Llano Bonito and other areas, are expected to generate new datasets that will better inform parameters relating to biological and physical elements.

The parameter selection performed by the sensitivity analysis could also be improved. Wallach *et al* (2001) developed a method for prioritising parameter importance in improving goodness of fit of the model, which could be applied to CAF2007.

### *4.4.3 INITIAL ASSESSMENT OF MODEL BEHAVIOR*

There appears to be a discrepancy between CAF2007 modelling of fertilization and the information reported by farmers. Data on reported fertilizer uses and yields in Chapter 1 tended to show a linear relationship between these two variables, even at extremely high levels of fertilization (400 kg of N/ha/yr). In contrast, CAF2007 is has very little sensibility to fertilizer applications at this level, behaving as if the coffee fields are over-fertilized. We suspect that the reality lies somewhere in between; yields reported by farmers may present some inaccuracy (as well as biannual oscillations of yield influencing the data) but the model would also benefit from improved sensitivity to levels of applied fertilization.

# CHAPTER 5

# EVALUATING THE USEFULNESS OF A PARTICIPATIVE APPROACH INCLUDING A NUMERICAL MODEL FOR DESIGNING CROPPING SYSTEMS

## 5.1 INTRODUCTION

Cropping system design aims to propose appropriate, sustainable and holistic solutions to agri-environmental situations. This is achieved by formulating cropping systems with farming practices that lead to improved agronomic performance and decreased environmental impact (Meynard *et al.*, 2001). However, in order to it reach its intended impact, solutions must be proposed in a way that encourages adaptation and adoption of these practices.

We place ourselves in a context of family-based agriculture, where farmers own the land they grow their crops on and perform a significant part of the on-field workload. Farmers are the ones who will need to adopt and implement the changes in farming practices into their daily work. Changing practices has costs in terms of time for knowledge acquisition, work, financial resources and potential loss in production (Greiner *et al.*, 2009). Socioeconomic, cultural or human factors may also determine the willingness of farmers to take an interest in changing their practices (Salamon *et al.*, 1997; Mazvimavi and Twomlow, 2009).

Relative confidence in different sources of information and expertise on crop management must also be taken into account when seeking to present farmers with new information and suggestions (Solano *et al.*, 2003).

Cropping system design must not only demonstrate that farmers' needs are being met, but also be communicated in a way that allows them to make an informed choice. After all, changes in farming practices and techniques are ultimately evaluated on their actual performance in the field (Ashby, 1986). Science-led field trials are frequently used, but involving farmers offers better chance of transitioning from experimental to standardized farming practices (Le Gal *et al.*, 2010).

These challenges to CSD are further complexified by competing uses of agricultural land and demands for ecosystem services (ES) (Doré *et al.*, 2011). It can be particularly difficult to work in complex systems with more than one species or where multiple ES are interacting with other – e.g. synergies or trade-offs. In order to take into account these multiple factors and processes, two approaches are commonly used in cropping system design:

- Modeling approach which privileges the use of a model synthesizing scientific knowledge on the system and its function; can test out a large number of scenarios as well as many factors through trial and error (Bergez *et al.*, 2010). Models are useful for when looking at trade-offs between ecosystem services for either summarising all the interactions or looking at individual factors (Stoorvogel *et al.*, 2004a). However they may present difficulties at the implementation phase, due to lack of communication between researchers and farmers or model not being user-friendly and not useable by farmers.

- Participative approach, using farmer and stakeholder knowledge as the basis for design of cropping system (Stoorvogel *et al.*, 2004b). Highly specific scenarios can be designed and adapted to local issues, and communication with farmers and use of the outcomes can be improved (Mendoza and Martins, 2006). However, this approach lacks the diversity of variables and scenarios offered by modelling, as well as the precision offered by quantified processes and outputs. It also sometimes lacks real novelty, as farmers have little access to external information, outside from their local experience.

Combining the two approaches would allow us to test a larger range of farming practices, under variable conditions, as well as ensuring they meet the specific needs and constraints of farmers. An example of this is the "companion modelling" approach: models are designed with farmers inputting information on all the steps such as definition of system, choice of scale, processes, outcomes. Benefits are familiarity of farmer with model thus facilitating use but restricted to farmer knowledge (Prell *et al.*, 2007). Research on companion modelling already provides valuable insight on managing farmer-model interaction (Simon and Etienne, 2010).

Our objective is to go beyond this scope to integrate scientific knowledge in the form of numerical model. The model would become a tool by which quantitative variables are introduced in the discussion with farmers. The effect of farming practices on the cropping system, their costs and benefits, can be translated into numerical information (work hours, product costs, losses or gains in crop yield) that is more readily assimilated by the farmers (Carberry *et al.*, 2002). This can stimulate participatory sessions, providing a platform by which farmers can both explore processes and variables they were not aware of, as well as offering the opportunity to put forward ideas and questions to be tested with the model at little or no cost (Whitbread *et al.*, 2009). By working in groups of farmers with similar practices, farmers can also directly exchange opinions and information between themselves around model presentation and use.

For a numerical model to be successfully used in this context, its scope and level of precision must be carefully chosen.

The range of major environmental, climatic, and biophysical conditions of the study area must be taken into account in the model, as well as the range of farming practices for the cropping system in question. Model parameters must also be calibrated to ensure local conditions can be accurately simulated.

Agroforestry systems are good candidates for testing out this method. The combined culture of trees with another crop leads to complex, long-term interactions (REF). Coffee-based agroforestry systems are a good example of this: both trees and coffee are perennial crops with interactions occurring from one year to the next. Coffee is also a high-value crop, with recognized environmental impact, which is still grown in small-sized farms. This gives farmers an incentive to optimize their farming practices as well as the ability to implement the decisions they make.

As explained in chapter 2, erosion is a significant environmental issue in coffee crops planted on steep slopes in Costa Rica's Tarrazu valley. This issue is recognized by both farmers (see chapter 1) and the hydroelectric dam operators who are concerned by excess sediment load in rivers in watersheds where the major land use is coffee cultivation. Shade trees have a critical role in coffee systems, as they affect both soil erosion and coffee production. We wish to design cropping systems with shade trees that both provide acceptable level of harvest, but also protect soils from erosion at the plot scale. These cropping systems must also take into account the constraints and scope of farming practices, to increase their likelihood of being adapted and implemented by farmers. We propose to use a numerical model of the coffee agroforestry system, calibrated for the Llano Bonito area to work with local farmers on designing cropping systems that are adapted to their needs, constraints and means. We will focus on the relationship between shade trees, coffee production and soil erosion that has been developed throughout this thesis. Our research question is: Can a **numerical model** increase the **scope** and **detail** of **discussions with and between farmers** on the **effect of farming practices** on a) **general state** of the agro-ecosystem and b) the **trade-offs between coffee production and erosion**?

We approach this issue with an already existent model, CAF2007, which fits our study system and scale. CAF simulates the coffee agroforestry systems with trees and coffee plants, at the plot scale, for the Central America region. It includes N, C and water balance modules, as well as plant biomass (including coffee cherry production), a variety of management options, and daily climate data (van Oijen *et al.*, 2010b).

## 5.2 METHODOLOGY

The study area was the Llano Bonito watershed , presented in chapter 2.

The model used was CAF2007, described previously in chapter 3. To our knowledge this was the only existing numerical model that simulated both coffee and shade trees at the plot scale, and over a span of several years.

Before beginning interaction with farmers, model had to be calibrated using data from the study area (ref. Calibration chapter).

### *5.2.1 PARTICIPANTS SELECTION*

We performed a series of workshops with local coffee farmers reflecting the diversity of farming practices and environmental conditions, based on the approach used by Whitbread (2009).

Strategic groups were formed based on the typology from chapter 1 (Darré *et al.*, 2007). The typology in chapter 1 classified coffee plots around Llano Bonito into groups of plots with similar farming practices and other common characteristics. The four groups were considered to represent the diversity of farming practices and constraints in the study area. We wished to compose groups of farmers that reflected this diversity, which is why we based our selection of participants on the typology. Therefore, for a given group (e.g. group number 1), we selected farmers who, according to the local coffee technician, had at least one plot which fit the description for that group. Farmers who had several plots were asked to focus on the largest/most important plot that matched the characteristics of the group.

The four groups and their key characteristics were:

1. Low-input – low yield, low use of agrochemicals except for fungicide, few trees, west-facing slope
2. Labor intensive – very high yield, east-facing slope, high use of fertilizer, some may use avocado trees
3. Shaded agro-ecosystem – high tree density, east-facing slope, medium to high yield
4. Agrochemical-intensive – high yield, high use of all agrochemicals, west-facing slope, low tree density mainly consisting of Erythrina

Chapter 1 provides more detailed information n the characteristics in each group.

Yield records from the local coffee cooperative and information from technicians familiar with the local coffee growers were the sources used to search for potential candidates.

Selected candidates were interviewed before the sessions began. They were asked to select one coffee plot that fit the group description, and describe its characteristics and farming practices. Average yield for the past two years, agrochemicals used in the past year and in what quantity, density of shade trees and coffee plants, and species of shade tree present were recorded. Expressed interest in the workshops and availability to attend all sessions were also factors in the selection process. Due to previous collaboration with local farmers for interviews and fieldwork, the rate of farmers accepting the invitation to participate was 72%. The activity was described to the farmers as a series of interactive workshops using different tools to discuss coffee farming practices. Participation were thanked for their time with a small non-cash prize, given out at the final session.

Once all the participants for each group (4 or 5 farmers per group) had been selected and had described their coffee plots, the values for each farming practice and plot characteristic (recorded as quantitative variables) were averaged for the entire group. These mean values were used as a description of "average" farming practices and plot characteristics for that group.

The average farming practices and characteristics of plots for each group, was compared to the values obtained for the corresponding group in chapter 1. The new groups formed for this part of the study were supposed to be constructed based on the typology in chapter 1; this was a way of testing the similarities between the two. The basis for comparison were the variables listed in the bullet-pointed list above.

### *5.2.2 SESSIONS*

The objective of these working sessions with the farmers was to evaluate the effect of introducing a numerical model on the scope and detail of a discussion around design of cropping systems. A total of five sessions per group were held between May and August 2012; each session lasted on average 3 hours (15 hours total). The sessions would focus on design of cropping systems, making use of different tools to discuss:

- the general state of the agro-system and farming practices;
- the effect of shade trees on the agro-system, coffee production, and erosion;
- design of improved cropping systems with decreased erosion.

Time was reserved for gradual introduction of modeling concepts and the numerical model itself, CAF2007.

“Sessions” primarily refer to their content: due to different groups progressing at different rates, one session was sometimes not completed in a single meeting, in which case it was finished at the next one and directly followed on by the exercises of the next session.

<u>Session 1</u>: conducted without any model in order to obtain a **baseline reference**. The general state of the agro-ecosystem was discussed by performing a SWOT analysis (Strengths-Weaknesses-Opportunities-Threats) of the coffee plots. As each variable was explained, farmers were asked to complete the analysis individually on a sheet of paper; the results were them shared and discussed with the rest of the group. For each variable (strength, weakness, opportunity and threat) the group identified the three answers that occurred most frequently on their plots.

Based on the outcomes of this exercise, the group was then asked a) to identify changes in farming practices they would like to experiment with, and b) what practices they would put into place to decrease soil erosion, at the plot scale. As in the previous exercise, farmers were first given the opportunity to write down individual answers before sharing them with the group, and jointly deciding on a “top three” for each variable.

<u>Session 2</u>: use of a **conceptual model** of the coffee agroforestry system, designed in Chapter 1. The conceptual model represented the coffee-shade tree system in Llano Bonito; input factors were farming practices and environmental characteristics of the plot; outputs were plot performance criteria: yield, gross margin and reduction in erosion. The model was used to confirm or change the outcomes from the group discussions in S1a. In order to do this, the model developed in Chapter 1 was put up on a wall, using cardboards for each element and wool threads of different colors for linking them. The conceptual model was explained as a “representation of reality” and different processes in the model were explained as an example. Elements of the model were described as “things you find in your coffee plot” and the links between them, “one thing having an effect on the other”.

The final outcomes of the group discussion in S1 (top three changes in farming practices, and top three practices for erosion control decided by the group) were displayed next to the conceptual model. Farmers were then asked to explain the effect of each practice on plot performance by identifying the “pathway” of processes in the model that led to it. Farmers were informed they could change the conceptual model if they felt it did not reflect reality; they were invited to do this themselves or to direct the session coordinator as to what changes. Any change required group consensus before execution; each participant was asked if they agreed or disagreed with the proposed change. The final state of the conceptual model, and the changes made to it, was recorded.

While the outcomes of S1 were discussed and explained using the conceptual model, any changes in opinion – rejection, modification, or replacement of the outcome with a new one – were recorded.

<u>Session 3</u>: a selection of **numerical data** from chapters 1 and 2 was presented as a base for discussing the effect of shade trees on the cropping system. The following information was presented:

- Characteristics and farming practices of the groups of plots defined in the typology of chapter 1
- Effect of shade, slope aspect and coffee pruning on yield over 2 years
- Effect of shade on flowering timing and intensity, as well as cherry loss between flowering and harvest

- Effect of shade on water stress

A basic interpretation of data was provided. Farmers were then asked to relate these findings to their own plots and knowledge, and provide their own interpretation if needed. After giving a chance to each participant to vocalize their thoughts, the group was asked to reach a consensus. For the presentation of characteristics and farming practices of the groups of plots defined in chapter 1, each variable was rated by the group for accuracy in relation to their own plot – variables could be “representative”, “somewhat representative” or “not representative” (or “unsure”). For the tables and graphs presenting data on the effect of shade trees, the group was asked to formulate one or several sentences that summarized their agronomic interpretation of the data.

In a second part, each group was asked to define what the word “model” meant to them. The coordinator then presented a scientific definition of a “numerical model”, using simple agronomic models as an example. The examples were then built up to a simplified version of the CAF2007 model. If necessary, an alternate term was agreed upon by the group in order to ensure clear understanding of the nature and application of a numerical model. This part was retroactively included in the methodology after a debriefing session with other scientists present at certain sessions, upon discovering that some farmers were not comfortable using the word “model” in the intended context.

<u>Session 4</u>: the **CAF2007 model** was presented and farmers were encouraged to directly interact with it via a model handler to change parameters and launch simulations. CAF2007 was first used to describe the actual state of a coffee plot, representative of the group. A variety of outputs were simulated – coffee yield, erosion, nitrogen pool, water content in the soil, tree and coffee Leaf Area Index (LAI). Management parameters were progressively introduced to explain the effect of each of them. Farmers were also shown they could change climate data to one of the three weather stations described in chapter 2, representing various areas of the watershed with slightly different climates.

After an initial explanatory phase, farmers were asked to suggest simulations for the model; at first with no restrictions, then focusing on simulations that would test ways of decreasing soil erosion. Simulations that involved simple changes in parameter values were performed on the spot in order to encourage participation. Suggestions were recorded individually using a diagram representing the coffee field in its actual state (baseline) and the changes they wished to simulate with the model.

<u>Session 5</u>: simulation suggestions were processed in order to bring answers to the interrogations made by the farmers. For session 5, farmers were visited individually or in pairs. The outputs of the simulations they had suggested, both generally and those focused on erosion reduction, were presented to them. According to the complexity of the questions, single-factor changes were also simulated in order to demonstrate the different factors affecting the final output. Outputs were shown using a variety of relevant variables in order to explain the effect of the proposed changes. The outputs were interpreted and discussed, and each farmer was asked to evaluate,

a) Did these simulations accurately reflect cropping systems in reality, based on in-field experiences?
b) What changes they would be interested in implementing in their own field?

Due to time constraints, only nine farmers participated in the last session. At least two representatives of each group were included in this last step.

### 5.2.3 DATABASE ANALYSIS

All sessions were recorded, with due permission given by the farmers. At the same time, a second investigator (not the one leading the session) took notes on the exchanges between farmers. The recordings were eventually used to complete the notes, or to recall particular wording used by the farmers that were deemed particularly interesting.

A database was created in order to record the questions made by participants during the session. These questions were characterized using a variety of criteria:

- Originator (who said it, during which session, and in which group they are)
- Type of question – e.g. desire for information, idea for experimentation ("what-if?"), seeking advice
- Destination – to the session coordinator, other farmers, for the discussion tool being used, or written responses on paper
- Discussion tool involved – none (S1), conceptual model (S2), quantitative data (S3), CAF2007 model (S4 and S5)
- Variables used to formulate the question – biophysical elements of the cropping system, farming practices, environmental factors, and outputs
- Complexity – the number of variables used in the question was used as a gauge of the complexity of questions asked

A summary was made of questions complexity (average number of variables per question) and diversity (total number of variables mentioned by each participant in a single session).

## 5.3 RESULTS

### 5.3.1 ASSESSMENT OF CURRENT STATE OF CROPPING SYSTEMS

Table 5.1 below shows the average values of the variables chosen to represent the farming practices for each group of plots worked on by the farmers participating in the workshops. The data in the table corresponds to the averages of values given by farmers participating in the workshops. Complete details of practices for each farmer are available in the annex III.

Table 5.1 - Agricultural practices and plot characteristics for each group

| | Low intensity | | Labor intensive | | Shaded system | | Agrochemical intensive | |
|---|---|---|---|---|---|---|---|---|
| | Typology | Workshops | Typology | Workshops | Typology | Workshops | Typology | Workshops |
| Yield (tons/ha/yr) | 4.2 | 5.1 (2.1) | 8.9 | 8.9 (2.6) | 7.2 | 7.2 (2.4) | 8.1 | 9.3 (3.1) |
| Fertilizer (kg of N/ha/yr) | 186 | 154 (34) | 502 | 351 (55) | 327 | 387 (99) | 417 | 322 (102) |
| Herbicides (L/ha/yr) | 0.96 | 1.22 (0.8) | 0.80 | 1.04 (0.4) | 3.84 | 3.29 (0.9) | 4.48 | 4.41 (1.2) |
| Fungicides (L/ha/yr) | 0.93 | 1.41 (0.7) | 0.51 | 1.88 (0.5) | 0.29 | 1.84 (1.1) | 2.44 | 2.63 (0.3) |
| Shade tree density (# of trees/ha) | 288 | 106 (58) | 332 | 310 (74) | 539 | 479 (113) | 235 | 134 (67) |

| | | | | |
|---|---|---|---|---|
| Shade tree species present | Erythrina, banana and fruit trees | Erythrina, banana, and fruit trees | Erythrina, banana, avocado, fruit trees | mostly Erythrina |

The farming practices for the groups of plots in the typology of chapter 1, and the plots owned by the farmers participating in the workshop, differed substantially. There was no significant difference between the two in regards to weed control, both chemical and manual; nor was there with yield, which presents important annual variations anyways (see chapter 2). However, fungicide and fertilizer applications differed significantly ($F=3.32$, d.f. 1,$P = 0.03$ for fertilizer, and $F = 2.47$, d.f. 1, $P=0.05$ for fungicide). Fertilizer use was significantly smaller in the plots owned by participants in the workshops, while fungicide use was significantly higher except for the agrochemical intensive group, where fungicide use was already high in the plots from the typology.

Table 5.2 summarizes the outcome of the SWOT analysis each farmer made for their respective plots. The most frequently stated strengths, weaknesses (INTERNAL factors), opportunities and threats/constraints (EXTERNAL factors) are summarized for each group.

Table 5.2 - outcome of discussion without any model or numerical data

| **Group** | **Strengths** | **Weaknesses** | **Opportunities** | **Threats/constraints** |
|---|---|---|---|---|
| 1: low-input | • High soil fertility<br>• Good level of shade<br>• Good slope aspect | • Mycena attacks<br>• Soil erosion<br>• Low yields | • Increase shade tree density but also pruning frequency<br>• Increase application of fungicide | • Lack of time for pruning and other actions |
| 2: labor-intensive | • Good slope aspect<br>• High yield<br>• High quality | • Lots of weeds to manage | • Fertility could be improved by applying CaCl, applying organic matter, or better arranging pruning residues to cover soil | • Lack of qualified workforce<br>• Changes in coffee price |
| 3: shaded system | • Produces organic matter<br>• Few weeds<br>• Small trees, easy to prune | • Soil acidity<br>• Strong slope and erosion<br>• Pests and diseases in general | • Soil analysis and applying CaCl if needed<br>• Fertilize less but more frequently<br>• Increase frequency of tree pruning | • Humidity certain years |
| 4: agrochemical-intensive | • Good yield<br>• Ease of access<br>• Good soil with good drainage | • Mycena attacks<br>• Lots of stones | • Training to improve knowledge and practices<br>• New products, organic chemicals | • Increase in rainfall<br>• Increase in products cost |

The SWOT analysis revealed a wide variety of concerns and interests in the different groups. The most commonly cited issues were yield, pests and diseases, soil acidity, and costs of agrochemicals and labor. Erosion, or factors relating to it, was mentioned by all groups, but no groups spontaneously spoke of erosion control methods. Farmers assessed similar weaknesses or threats differently. For example, all groups mentioned the threat of production loss caused by fungus attacks. However, group 3 did not feel this was a major issue since “fungus attacks only affect the plot in bad (“wet”) years”. On the contrary, the low-intensity and agrochemical-intensive groups (both west-facing plots) clearly identified fungus attacks as a major issue.

The SWOT analysis also revealed different levels of agronomic management, with some groups already optimizing their management as best they can, while others recognized they knew what they had to do to improve their cropping system, but simply lacked the resources and/or organization. When the question about problems or bad characteristics of the coffee plot was asked to the labor intensive group, farmers generally felt that they “already do the minimum that needs to be done” (S1) and focused more on discussing opportunities for improvement.

Overall, the SWOT analysis mirrors some of the trends observed in chapter 1, in regards to groups 1 and 4 being more strongly affected by fungus attacks, and groups 2 and 4 being at higher levels of production and optimization of their cropping system.

### *5.3.2 MODEL PREPARATION*

Table 5.3 – parameters used to personalize the farming practices for each simulation.

| Parameter | Unit | Range |
|---|---|---|
| Amount of N applied | Kg of N/ha | 0-500, up to 4 applications at any date |
| Shade tree species | - | Erythrina poeppigiana<br>(other tree species not used in study area) |
| Fraction of shade tree pruned | Kg of C/ha – branches and leaves | 0-100% |
| Shade tree pruning dates | days | After initial pruning date, fixed recurrence determined by number of days (e.g. 182 days for biannual pruning) |
| Fractions of shade tree thinned | Kg of C/ha – branches, leaves and trunk | 0-100%, as many repetitions as needed |
| Shade tree thinning dates | days | After initial thinning date, fixed recurrence determined by number of days |
| Fraction of coffee pruned | Kg of C/ha – wood and leaves | 0-100%, as many repetitions as needed |
| Coffee pruning dates | days | After initial pruning date, fixed recurrence determined by number of days |

Table 5.3 above shows which parameters of the CAF2007 model were used to prepare the model simulations. These parameters allowed the farmers to test out different farming practices in relation to fertilization, shade tree management, and coffee pruning.

### *5.3.3 RESPONSE TO DISCUSSION TOOLS*

A total of 195 distinct questions were made by the participants during the five sessions. As the sessions advanced and new tools for discussion were progressively introduced (e.g. conceptual model, field data on effect of shade trees, numerical model), the questions increased in the diversity of variables used to formulate them. Variables for the questions database shows significant differences between sessions ($F=6.87$, d.f. 1, $P<0.01$) as well as in between groups for complexity of questions and variety of variables used (see table 5.4 below).

Table 5.4 – complexity and diversity of questions made by participants of different groups during S1, S2, S4 and S5

| Group | Complexity (mean # variables/question) | | | | Diversity (mean # of variables mentioned/participant) | | | |
|---|---|---|---|---|---|---|---|---|
| | S1 | S2 | S4 | S5 | S1 | S2 | S4 | S5 |
| Low intensity | 1.0 (0) | 1.9 (0.4) | 3.5 (0.8) | 3.9 (0.5) | 5.2 (1.2) | 6.5 (1.5) | 10.7 (2.2) | 7.4 (2.0) |
| Labor intensive | 1.3 (0.6) | 1.8 (0.4) | 4.5 (0.9) | 4.6 (1.0) | 8.4 (1.8) | 11.2 (3.5) | 12.0 (1.8) | 11.8 (1.9) |
| Shaded systems | 1.0 (0) | 2.1 (0.7) | 3.9 (0.6) | 4.7 (0.8) | 6.3 (0.8) | 9.6 (1.4) | 10.3 (2.0) | 10.1 (2.2) |
| Agrochemical intensive | 1.0 (0) | 2.3 (1.4) | 4.1 (1.1) | 4.7 (0.6) | 6.0 (1.1) | 7.3 (2.8) | 9.6 (1.4) | 11.0 (2.5) |

Most groups saw an increase in complexity and diversity of questions asked as the sessions went on and the time spent on discussions instead. Diversity did not significantly increase between S4 and S5, since the discussion during S5 was focused on specific questions already asked by the farmers, as well as erosion reduction (our main research question). Using the conceptual model as a discussion tool in S2 did trigger an increase in the variety of variables being discussed, since the model mentioned new variables that had not been mentioned before. In the same way, presenting the CAF2007 model function and simulations in S4 introduced new variables (e.g. nitrogen leaching, root biomass, runoff) which led to a significant increase in the complexity of questions asked.

Changes were also observed in the terms and vocabulary used in the questions. One participant in group 3 initially identified “soil fertility” as being a significant issue for their coffee plot. After introduction of the conceptual model, the participant referred to “soil organic matter” and “nutrients”. After working on the CAF2007 model in S4, the participant comfortably discussed levels of “nitrogen in the soil” in their plot. This allowed the farmer to ask specific questions regarding nitrogen gains and losses in the cropping system. Similarly, “erosion” was frequently mentioned in the initial sessions but it was only after introduction of CAF2007 and presentation of simulations that farmers narrowed down on “loss of soil per m$^2$” as well as “runoff”. Nevertheless, this change in vocabulary was not linked to any change in the farming practices suggested to manage these elements.

The themes mentioned initially by the farmers were compared with themes discussed at the group scale after presentation of the numerical model (S4) and after some feedback concerning the model simulations (S5).

Table 5.5 – Major themes mentioned by participants during workshop

| Group | S1 | S4 | S5 |
|---|---|---|---|
| Low intensity | Cost of labor and agrochemicals | Soil fertility, erosion, shade tree management | Economic analysis of fertilization, coffee density, erosion |
| Labor intensive | Availability and quality of workforce | Climate, nutrients in soil, gross margin, fertilization | Shade tree management for leaf litter production, fertilization |
| Shaded systems | Soil acidity, application of Cacl | Climate, nutrients in soil, pests and disease | |
| Agrochemical intensive | Pests & diseases, Mycena & others | Weather, impact of climate on management decisions | Different fertilization patterns, |

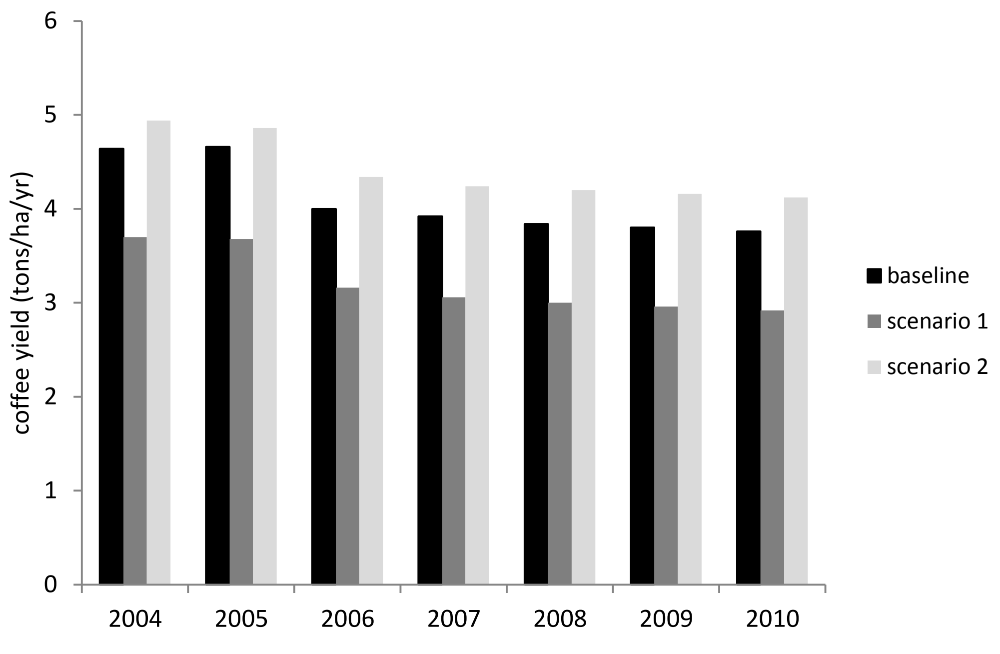
### *5.3.4 EVALUATION OF SCENARIOS AND FEEDBACK*

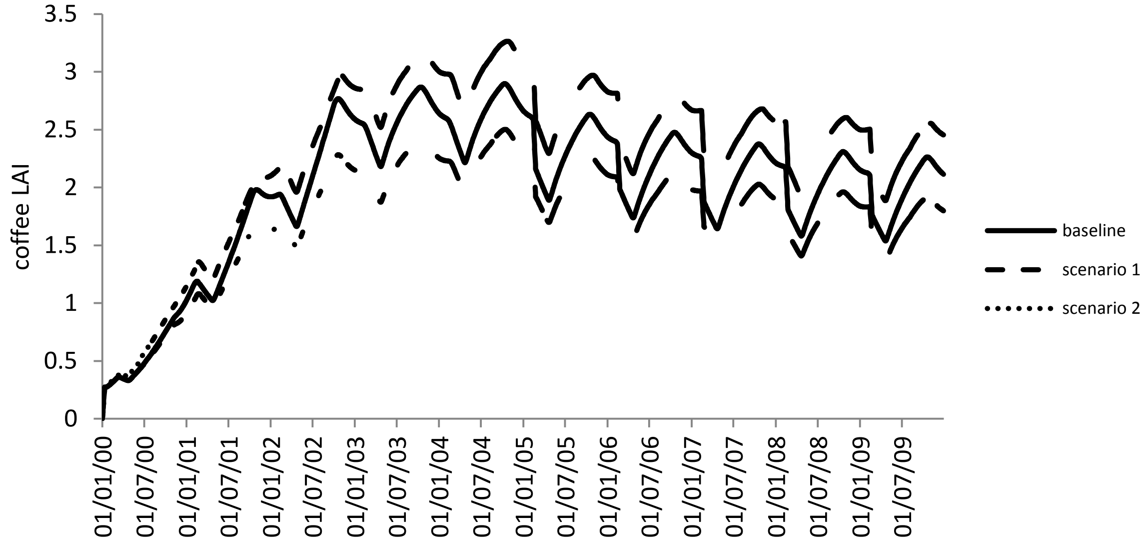
Table 5.6 shows an example of a cost/benefit analysis, applying various levels of fertilization with the low-input group during S4. All groups expressed interest in making sure they "*bought the right amount of fertilizer*" (S2, group 1). All farmers agreed that increasing fertilizer application also increased yield up to a certain threshold. In S4, the CAF2007 model was used to test the cost-efficiency of various levels of fertilizer application, using a simple price multiplier to translate total nitrogen application into costs of fertilizer bags, and yield into income.

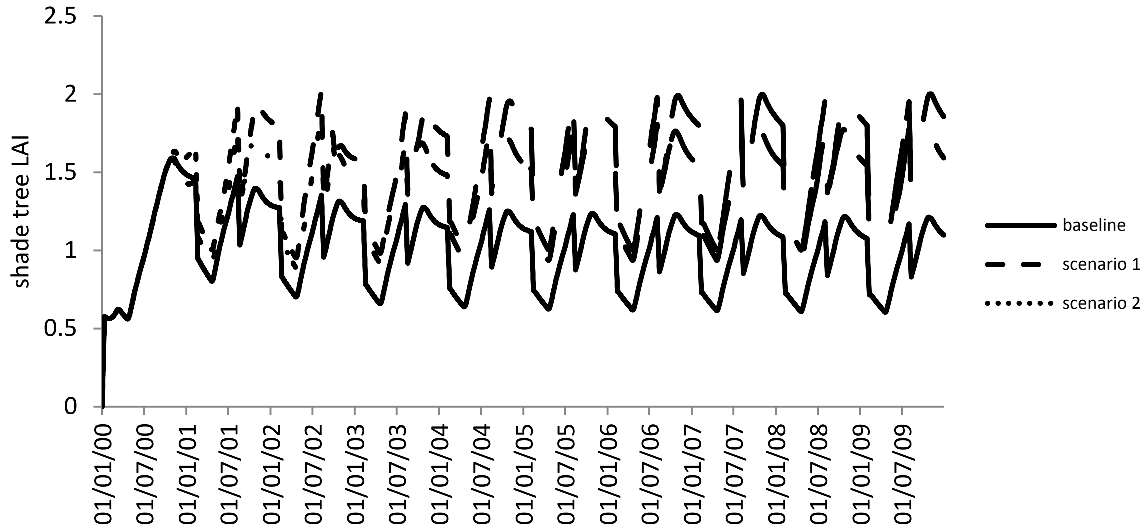
Table 5.6 – simulation of cost/benefits of different levels of fertilizer application

| Total N applied (kg/ha/yr) | 0 | 40 | 90 | 150 | 250 | 350 |
|---|---|---|---|---|---|---|
| Cost (USD/ha/yr) | 0 | 145 | 326 | 543 | 906 | 1 268 |
| Income (USD/ha/yr) | 1 718 | 2 266 | 3 041 | 3 760 | 4 552 | 5 078 |
| Gross margin (USD/ha/yr) | 1 718 | 2 121 | 2 715 | 3 217 | 3 646 | 3 810 |

Figures 5.1 below shows, based on questions asked by a farmer from the low intensity group, an example of two scenarios that are compared to a baseline situation . Scenario 1 increased shade tree density from 250 to 500 trees/ha and fraction of tree biomass pruned biannually from 0.6 to 0.4. In Scenario 2, these same changes are kept and application of nitrogen through fertilization is increased from 180 kg to 360 kg of N/ha/yr. Simulations are run for 10 years on newly planted coffee which begins to produce harvestable coffee in the 3rd year. The model calculates that increasing shade tree biomass leads to lower levels of soil loss through erosion, but also lowers coffee Leaf Area Index and coffee yield. Doubling the amount of nitrogen applied leads to an increase in both tree and coffee LAI, and a substantial increase in simulated yield.





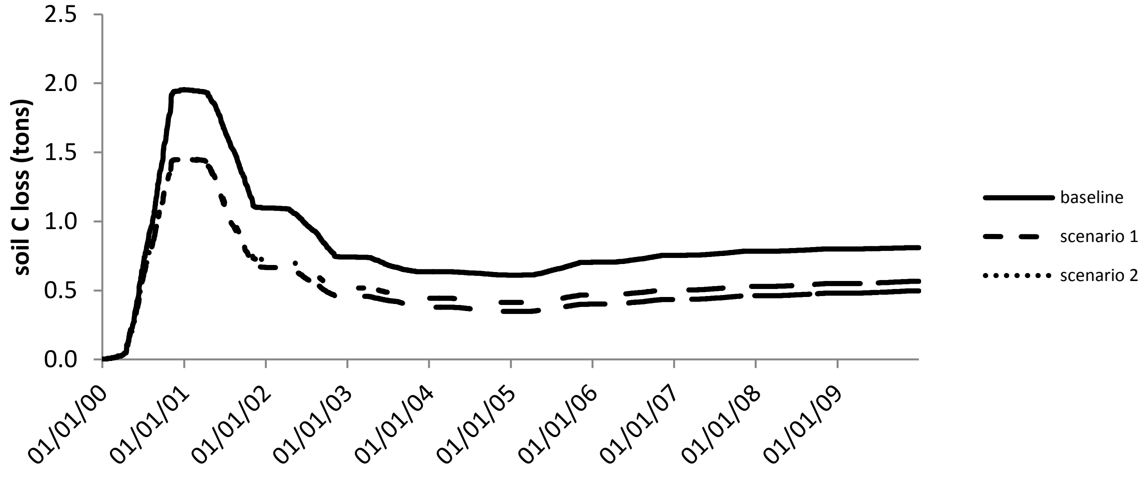




Table 5.7 below summarizes the evaluation of the accuracy of the model simulations by the farmers, who were asked to describe, for every output shown, whether the model simulation corresponded to their own knowledge and experience.

Table 5.7 – participant perception of model performance on several variables

| Variable | % agreed model simulated accurately | Farmer perception |
|---|---|---|
| Fertilization (applied kg of N/ha/yr) | 55% | Model was not sensitive enough and should show stronger response to increases in fertilization, especially at lower levels |
| Shade tree density (# trees/ha) | 33% | Did not agree with model reaction of simulated decreased yield with increased shade tree biomass, even at low levels: consider that “shade trees help the coffee produce more” and “help the plant live longer” |
| Shade tree pruning (% of leaf and branch biomass removed) | 55% | Effect of different pruning types (upper branches, lower branches) not taken into account |
| Coffee LAI | 88% | One disagreement noting that coffee LAI decreases due to removal of foliage from coffee harvesters |
| Mineral N pool (kg of N/ha in soil) | 100% | Agreed on accuracy of N pool but questions on importance of other minerals |

Table 5.8 below summarizes the reactions of participants to session 5 to the simulations proposed. At least two representatives of each group were interviewed, either on an individual or paired basis. The questions asked were varied and several scenarios were simulated each time; the table shows the most discussed scenario in each meeting. Out of the nine farmers, five manifested a desire to implement some or all of the discussed changes in their field or in part of their field. Out of those that did not identify changes they would like to implement, two openly expressed disagreement with model outputs and two did not find any change that they could implement that would be feasible for them.

Important to discuss coincidences and disagreement between farmers and model. The way they are representative has to be mentioned in the method paragraph otherwise say there that they are either volunteers or  whatever else (chosen by the group or by you)

The changes that farmers considered for application in the field were generally related to increasing the frequency of fertilizer applications, which was shown to lead to a higher mineral N pool and improved yields. Increases in tree biomass (the management factor leading to greatest decrease in erosion in the model) were generally linked to an increase in tree density with increased pruning frequency and/or intensity, or the reverse. CAF2007 systematically simulated increased shade cover as having a negative effect on yield. On the other hand, farmers identified shade trees as being beneficial especially in relation to coffee plant longevity, full-sun coffee plantations requiring much more frequent pruning (followed by longer regrowth times before the plant reaches full production again).

Table 5.8 - Reactions of participants of session 5 to changes in management

| # | Group | Baseline scenario | Changes made | Outputs from simulation | Evaluation of outputs |
|---|---|---|---|---|---|
| 1 | Low intensity | 3x60 kg of N applied/yr; prune 60% of shade trees (on average) in May/Oct | 40, 46 and 60kg of N, prune shade trees in March/Sept, increase March pruning to 80% | Increase in yield, from 4.15 to 5.26 t/ha/yr on average over 7 years; changes lead to lower tree LAI but higher coffee LAI; runoff initially higher but lower afterwards; nearly double amount of mineral N | Interest in higher yield but concern about higher costs of fertilizer; not convinced that decreasing shade cover is unsustainable - "less shade will tire the plant in the long term" |
| 2 | Low intensity | Annual coffee pruning rate of 10%; 3x62kg of N applied/yr; 150 trees/ha | Increase annual coffee pruning rate to 20%; increase N to 62, 62 and 83kg of N; increase shade to 200 trees/ha | Yield decrease from 4.45 to 4.21 t/ha/yr especially due to lower yields later on; soil erosion | Would increase fertilizer and tree density but not prune more; interested in seeing more organic matter in soil; effect of Mycena unsure |
| 3 | Labor intensive | 300 trees/ha pruned three times/yr in June, Sept and Nov; 82/82/58kg of N applied/yr | Prune trees twice/yr (3 weeks before flowering then in Aug) during a year with very hot dry season; apply fertilizer in 58/58/58/58 kg | Yield goes from 7.25 to 7.57 t/ha/yr on average; increased tree LAI but cut just before flowering; late fertilizer application helps cherry growth | Seems logical, will try applying fertilizer in smaller quantities and experiment with different shade tree pruning frequencies |
| 4 | Labor intensive | Shade trees pruned twice/yr (70%); annual coffee pruning rate 15% | Prune trees every 2 months (20%); increase coffee pruning rate to 25% but less frequent | Shade tree LAI significantly increased; yield decreases from 6.85 to 6.21 t/ha/yr; soil erosion three times as low | Easier to manage only two tree pruning events a year, also more efficient; will try other erosion control methods (e.g. terraces) |
| 5 | Labor intensive | 300 trees/ha; pruned twice a yr; 3x58kg of N applied/yr | Increase shade tree density to v. high levels (1000 trees/ha) with 4 prunings/yr; decrease fertilizer applied to 3x50kg; hotter climate | Yield decreases by 2.14 t/ha/yr in normal climate; decreases by 1.57 t/ha/yr if climate increases by 1.5°c | Will try to apply slightly less fertilizer; will plant more trees if it gets hotter |
| 6 | Shaded systems | 3x50kg of N applied/yr; 600 trees/ha; annual coffee pruning rate 20% | Reduce shade to 300 trees/ha; apply 83, 83 and 62kg of N; decrease annual coffee pruning to 10%; effect of increasing precipitation one year | Yield increased from 5.15 to 7.30 t/ha/yr on average; erosion significantly higher | 10% pruning with fewer trees while sustaining higher yields not considered realistic |
| 7 | Shaded systems | 800 trees/ha pruned three times a year at 40%; 3x83kg of N applied/yr; | 66, 50 and 83kg of N applied/yr; first tree pruning 3 weeks before coffee flowering; go to 600 trees/ha and 50% pruning rate | Yield increased from 7.22 to 7.41 t/ha/yr; erosion not significantly higher; increased N mineral pool | Encouraged by simulation outcomes, will try to decrease fertilizer application |
| 8 | Agrochemical intensive | 3x75 kg of N applied/yr; trees pruned 70% three times a yr | Apply 4x50kg of N/yr; decrease shade tree pruning to two times a year 60% | Average yield increased from 6.96 to 7.20 t/ha/yr; yet mineral N pool significantly increased and soil erosion decreased | Will try fertilizing in 4 times instead of 3 but with same total amount; still lacking information on effect of weather on N mineralization rate |
| 9 | Agrochemical intensive | 120 trees/ha pruned twice a yr (70%); annual coffee pruning rate 25% | Increase shade to 300 trees/ha pruned three times a yr (50%); decrease coffee pruning rate to 15% | Average yield decreased slightly; tree LAI significantly increased from max of 1.65 to 2.24; erosion significantly reduced | Appreciates decrease in soil erosion but model predicts no yield gain + effect of Mycena fungus loss; for now will keep trees same |

## 5.4 DISCUSSION

### *5.4.1 NUMERICAL MODEL AS AN EDUCATIONAL TOOL TO EXPLORE PROCESSES AND TRADE-OFFS*

Using various tools for discussion, technical discussions on design of cropping systems with coffee farmers was improved in terms of precision and variables used to describe the system and its processes. Using a conceptual model for visual reference led farmers to use new variables to describe the systems and processes they had mentioned initially. The numerical model CAF2007 brought quantitative variables and mathematical calculations into the discussion, such as cost vs benefit of different levels and timing of fertilizer application. It also helped us explore the factors behind such processes such as provision of nitrogen from shade trees, and relationship between LAI and erosion and production which may lead to trade-off situations. These processes sometimes differed from farmers' initial understanding, so in this sense the model was able to enrich their understanding of biophysical processes in their coffee fields.

Fertilization remained a frequently mentioned theme and was easier to begin work on, especially due to the easily quantifiable aspect on calculating profit on fertilizer expense vs. yield income. The discussion on gross margin and economic balance yielded the many questions and responses within all groups. This acted as a "hook" to get farmers to realize the potential of the numerical model, facilitating subsequent work on questions regarding erosion: the ability of the model to answer at least *some* of the "burning questions" from the farmers was significant in ensuring their interest (and sometimes enthusiasm) in its use. Over the course of the sessions, farmers took new variables into account that were not discussed previously; previously expressed interest in "organic matter" and "fertility" was followed through by interest in discussing mineral N pools, N loss and C loss in the model. The introduction of extra variables, such as soil C loss and N leaching to respond to farmers questions was also well-received.

The theme of erosion vs coffee production (our theme of choice) was not one that came up in all groups spontaneously but once it was introduced generated interest in all groups. Most groups responded with interest to graphics showing loss of sediment per square meter, correlating it with loss of soil organic matter and fertility. Demonstrating the loss of nitrogen by soil erosion (calculated at a fixed C/N ratio) had a particularly significant impact in explaining that loss of soil also means loss of nitrogen, and motivating farmers to take an interest in decreasing erosion at the plot scale.

Farmers with more intensive farming practices tended to understand model function and outputs more quickly than the low intensity and shaded systems group. In the end, the latter two groups required an additional session in order to complete session 4. It is possible that intensive producers (who invest higher amounts of time and money, thus take on higher risks) had more incentive to learn about a tool that might help them minimize risks associated with experimentation.

### *5.4.2 MODEL PRESENTS CONSTRAINTS AND LIMITATIONS*

Due to working with a pre-existing numerical model, the scope of the questions answered by simulations had to be drastically reduced from the initial pool of questions from the participants. This was expected, since in order to gain in precision of analysis, we could not include all factors. At the beginning of S4, limitations of the model were clearly defined and several issues, such as soil pH, effect of combining *E. poeppigiana* with banana-type trees (*Musa* family), and especially effect of pests & diseases, were set aside. The concerns and priorities expressed by the farmers were sensibly different from one group to another. For example, the “agrochemical-intensive” type expressed interest in the outputs of model simulations in S5 but all three farmers interviewed expressed hesitations in experimenting with the changes since *Mycena citricolor* fungus attacks were likely to affect the outcome. This can be related to environmental conditions seen in the groups, where the low intensity and agrochemical groups tend to have more unfavorable slope orientations for Mycena attacks, the most common fungus causing damage to coffee plants in the area (Avelino *et al.*, 2005).

The model also showed limits in the way it handled farming practices, as farmers sought more precise recommendations on coffee and shade tree pruning (branch/shoot selection), fertilizer application in relation to rainfall (nitrogen balance is not affected by rainfall in the model), and architectural aspects of managing the plantation (locations for replanting new coffee, competition in between shoots). This sometimes left farmers in agreement with basic principles of increasing or reducing biomass, foliage, etc. but asking more questions on how. This could also be interpreted as an interest in more precise, plant-level models in order to achieve a greater understanding of plant function, such as the MAESTRA model. When studying the effect of shade trees in a region where climate and production of coffee is already near optimal, integrating the die-back effect caused by overproduction would be needed to truly evaluate the long-term effects of shade. This was frequently mentioned by farmers who remembered the large-scale shade tree removal in coffee plantations in the 80’s, and the highly negative consequences on coffee plant longevity (Rice, 1999).

Another area that would have benefitted from coupling an additional model for extra information was in terms of erosion modeling. CAF2007’s erosion module does not account for a large number of crucial factors such as soil structure and roughness, presence of live and dead vegetative matter, and the management of residues from shade tree and coffee pruning (Lin and Richards, 2007; van Oijen *et al.*, 2010b). Any significant plan for erosion management at the watershed scale must also take into account wider factors such as land use, pathways and roads, variations in slope and drainage (Gomez-Delgado *et al.*, 2011). Future studies would probably need to combine the necessary models in order to ensure the ecosystem services and cropping systems concerned are simulated to the degree of accuracy required.

### *5.4.3 HOW HAS THE MODEL HELPED ADVANCE DESIGN OF CROPPING SYSTEMS?*

Taking into account the benefits and limitations of using a numerical model in this participative context, we asked ourselves what had the numerical model brought that could not have been achieved through advanced technical discussions supported by qualitative and quantitative data. The numerical model showed its limits in terms of scope and precision of the questions it could answer; and many processes and variables explored in the later sessions could arguably have been discussed with data and the support of a conceptual model. However, the relative ease and speed with which CAF2007 was able to integrate a large number of factors was probably the most convincing aspect of its performance with the farmers. Its ability to simulate “invisible” variables (referring to mineral nitrogen pools, biomass of different plant organs, and soil water content) was also appreciated. Many compared the model simulations to the soil analysis for detecting nutrient deficiencies sometimes performed by the local technician; “the computer shows us things we can’t normally see”.

This study would require follow-up in the near future in order to see whether farmers followed up with changes in their farming practices.

# CHAPTER 6

# GENERAL DISCUSSION AND PERSPECTIVES

The aim of this final chapter is to:

1. Critically discuss the methodological framework used in this thesis and assessing its limitations
2. Evaluate the scientific outcomes of this thesis, the applicability of the method in other situations, and propose new avenues for research on cropping systems design (CSD) both for general purposes and for the study site
3. Formulate agronomic recommendations for the improvement of erosion control at the plot scale in the Llano Bonito watershed

## 6.1 USING MODELS FOR WORKING IN CROPPING SYSTEM DESIGN

### *6.1.1 CONCEPTUAL VS NUMERICAL MODELS*

In chapters 2 and 5 we have seen the potential applications of a conceptual model and a numerical model of coffee agroforestry systems. In chapter 2, the conceptual model was primarily used as a tool for identifying the variability of trade-offs between erosion control and coffee production, and its impact on the suitability of different erosion control practices. It was also used in chapter 5 as a tool for discussion with the farmers who participated in the workshops, before introducing the numerical model. The conceptual model helped make explicit some processes and effect of certain practices that the farmers had mentioned previously. It also allowed to pinpoint the elements of the agroforestry system which affected both coffee production and erosion, in order to steer the discussion towards resolution of trade-offs.

In the last two sessions described in chapter 5, the numerical model CAF2007 was introduced and work on design of cropping systems with farmers centered around model outputs. The numerical model was able to take the discussion to new levels, thanks to a) higher detail and precision of the various processes encountered in the model, and b) introduction of quantitative data. Introducing new variables and detail in soil and plant processes increased the technical precision of discussions; and the use of quantitative variables allowed the discussions to progress towards more realistic evaluations of potential cropping systems. More importantly, using a more technical jargon and actual numbers led to more factual and objective discussions which facilitated the communication and understanding between farmers and researchers.

So what lessons can we draw from this study about the use of conceptual and numerical models? Each of them offers benefits and constraints; what do the conclusions of these studies tell us about the appropriateness of each type of model for cropping systems design?

The workload involved in the preparation of a model is a fundamental criteria in model choice – in order to be efficient, analyses must not only be relevant and answer the questions at hand, but they must do so in a timely manner (Antle and Valdivia, 2006).

Potential workload in numerical models is of two natures. Our first observation, based on our work with CAF2007, is that accurately simulating outputs with numerical models requires precise parameterization of the model. Yet this can only be achieved rapidly if previous datasets or calibrations from similar areas and production systems exist. In the case of certain crops and climates, substantial research has already been done and high-quality models are available which can be applied quite easily – such as the Yield-SAFE model developed for agroforestry systems in temperate climate (van der Werf *et al.*, 2007). Data from tropical climates tends to be harder to obtain, yet models of complex/multispecies systems require even more data than usual in order to take into account interactions are different types of scales: agronomic (intra- and inter-species interactions), geographic (plant, row, field) and temporal (seasons and years, in the case of perennial plants). Experimental and statistical techniques do exist to facilitate the obtention of parameter values from datasets, e.g. Hochmen *et al* (2001) and Antle and Valdivia (2006), or for the sharing of available data (Matthews and Stephens, 2002). In addition to parameterization, modifications to the model structure and function may be necessary in order to include information specific to the study object. This can become extremely time-consuming and is almost equivalent to designing an entirely new model. Even apparently simple processes, such as coupling two existing models, can be a heavy task. Some frameworks such as FARMSCAPE (Carberry *et al.*, 2002) have been developed specifically for this kind of situation, making the coupling and combination of different models easier. As with parameterization, the weight of this constraint is dependent on what information and tools are already available.

For conceptual models however, there exist generic frameworks, as exemplified by Lamanda *et al* (2011), which allow a speedier design of suitable cropping systems. We ourselves were able to follow these guidelines and rapidly built a conceptual model that answered our needs and was subsequently used in our research. The only delay in model construction was caused by the decision to wait for a second year of data in order to decrease uncertainty of the data obtained. Furthermore, we were unable to obtain data on soil erosion in time for writing, due to the nature of this phenomenom which makes short-term estimations meaningless; without this constraint, it would have been easier to document the trade-offs between services. Lower data requirements significantly lighten the burden of preparation for conceptual models, allowing our cropping system design efforts to be more responsive and adapted to the study area.

The two types of model are not mutually exclusive. As pointed out by Lamanda *et al* (2011), conceptual models can – and often do – form the basis for the construction of numerical models. After overcoming the data requirements, the resulting numerical model would be more suitable to answer the agronomic questions posed. For example, construction of a numerical version of the model presented in chapter 1 would have allowed us to integrate the trade-off between shade trees and incidence of fungus attacks. Rodrigues (2012) has developed a numerical model, which focuses on this particular aspect of coffee agroforestry system. Admittedly, the use of CAF2007 limited our research in certain areas but remained the most effective tool within the time frame and resources of this thesis.

The conceptual model was a useful tool within its range of possible applications, but it took a numerical model to trigger significant increases in the complexity of discussions around CSD. In this case, the role of the conceptual model was for CSD but for improving our own understanding of the cropping system, its constraints and trade-offs.

### *6.1.2 LIMITATIONS AND QUALITIES OF CAF2007*

Even a model which fulfills the criteria mentioned above, can present significant limitations. At the time of choosing the numerical model to use for this thesis, CAF2007 presented many advantages: it was fully developed and ready for use; it was built on the appropriate scale and integrated basic climate and management variables as well as shade trees; it was specially developed for Central America using commonly found shade tree species and management practices. Yet we found significant limitations to its application in chapter 3 – lack of detail in simulation of coffee physiology, not including banana tree shade, and lack of feedback from one harvest to the next to simulate the biannuality of coffee production (and the “die-back” effect). The latter variable ended up being particularly important, as it was the means by which farmers tended to explain the long-term benefits of shaded systems. Instead, the model consistently simulated lower yields with higher shade tree densities, which did not match farmers’ experiential knowledge; our own field data showed no significant effect. Modeling of the effect of yearly oscillations in production on coffee plants – as well as the physical defoliation during coffee harvest – would therefore be the most urgent change we would make to the CAF2007 model. Van Oijen *et al* (2010b) noted the limitations regarding simulation of yield variations in the initial evaluation of the model, along with the fact that no data was available to quantify the importance of this effect at the field scale. Our own data is insufficient, since two years is too short a time frame to properly evaluate this effect. However, feedback from farmers in chapter 5 encourages us to think that yield oscillations do significantly differ between shaded and unshaded plantations, and that a larger-scale study of this phenomenon would be worthwhile.

Despite these limitations, qualities of the model were also pointed out by the farmers. There was no lack of ideas for simulations, especially with single-factor comparisons - normally not possible on the field. Whitbread *et al* (2009) noted that in comparison to field trials, where local environmental factors may cause interference with results, models offer a “cleaner” way of examining effects of changes to the system on specific variables. Although models for complex cropping systems such as coffee/shade tree systems must account for many interactions, it is possible that the omission of certain processes and simplification of others might have been an advantage in this regard. Comparing the use of different numerical models (Van Oijen, 2008) might shed more light on this issue.

## 6.2 APPLICATIONS OF THE METHODOLOGICAL FRAMEWORK

### *6.2.1 IMPLICATIONS OF CHARACTERISTICS OF THE STUDY SITE*

Agronomic knowledge of coffee production is widely shared (Cerdán *et al.*, 2012). In Llano Bonito, most coffee growers have at least one generation of experience in coffee farming. The local cooperative and processing plant is in existence since 1972 and is a major source of information and education on coffee production. There remain few “low hanging fruits” in terms of improvement of crop productivity. Coffee from the Llano Bonito valley is sold well above average market price for hard bean Arabica coffee, due to its recognizable qualities marketed under the "Tarrazu" appellation. Certain years, gross margins can even run into the thousands of dollars per hectare (chapter 2). Decreases in production through change in farming practices are costly. Furthermore, farmers are already vulnerable due to the high cost of yearly investment in purchase of agrochemicals (using their savings or, more frequently, on credit), as well as fluctuations in coffee sale prices.

In this agronomic context, propositions of changes in farming practices that might negatively affect coffee production therefore have to be constructed carefully and supported by hard evidence. This gave us the opportunity to a) propose solutions that relied on increased use of ecosystem services (Doré *et al.*, 2011), and b) use sophisticated tools to precisely assess the impact of changing farming practices on coffee production.

### *6.2.2 SCIENTIFIC OUTCOMES AND WIDER APPLICATIONS*

One objective of this thesis was to produce outputs that could be used to continue the prototyping process with the application of changes in farming practices as in-farm field trials, or perhaps even scientist-controlled experimental trials. With the farmers that participated in the last work session with CAF2007, possible changes in farming practices that they could put into place were identified. A follow-up study returning to those farmers could identify which practices were or were not applied or adapted in part or all of their coffee fields. Interviews on farming practices, following the same format than in chapter 1, would allow for a numerical analysis of practice changes between the study years, 2009 and 2010, and the time of follow-up. The ongoing scientific efforts of other students and researchers in the Llano Bonito valley, as well as continued collaboration and communication with farmers and the local cooperative, will hopefully facilitate this.

Coffee systems in Llano Bonito are a relatively intensive form of coffee production. The methodology developed in this thesis could also be applied to less intensive coffee systems. When yield levels are already low, the potential amount of yield lost due to changing farming practices is also lower; compensation by the way of payment for ecosystem services is less costly, and there are fewer trade-offs (Muschler, 2001). Additionally, coffee systems with low productivity are associated with higher levels of shade tree diversity (Perfecto *et al.*, 1996), which makes numerical modeling even more difficult - CAF2007 can currently only simulate once species of tree. Simulating multiple species would require taking into account spatial heterogeneity (both vertical and horizontal) – either creating an extremely complex model which couples together model of several different species, or drastically simplifying the modeling of each species (Roupsard *et al.*, 2008). Certain module-based farm-scale models such as FARMSCAPE (Carberry *et al.*, 2002) or the APSIM framework (Keating *et al.*, 2003) provide an example of how mixing of several crops might be simulated.

## **6.3 CONCLUSIONS ON EROSION CONTROL IN LLANO BONITO**

### *6.3.1 THE ROLE OF SHADE TREES*

The various sources of information in this study (numerical model, field data, interview and work sessions with farmers) provided a variety of information on the effect of shade trees on the agroforestry system. CAF2007 simulated positive relationships between *Erythrina* shade tree density and reduction in loss of soil C; but a negative relationship between *Erythrina* density and coffee yield, even at very low densities. As noted above, this behavior is not consistent with information from farmers in the work sessions, where shade trees were repeatedly pointed out as beneficial for both soil conservation and yield – or, at least, sustainability of yield by decreasing pruning frequency and intensity. The data from chapters 2 and 3 provided valuable insight into this trade-off. Indeed, although the field data from 2 successive years did not show a significant relationship between yield and shade cover, it did demonstrate the benefits of *Erythrina* shade on variables related to soil conservation. The strong influence of the “year” and “site” factors on yield also demonstrated the importance of annual variations and local environmental conditions in regulating the relationship between shade tree cover and coffee production.

The role of the *Mycena* fungus in the relationship between shade tree cover and coffee yield, already noted by Avelino *et al* (2007a), was highlighted by the data from interviews with farmers in chapter 2. During very rainy years, this fungus is a constraint for most farmers who prune their trees heavily in order to decrease the ambient humidity that favors fungus development. In drier years, this constraint is limited to plots with naturally humid conditions only. In the study area, humidity was strongly linked to slope orientation; a larger number of study sites might have given us a better overview of this effect. In any case, including a sampling protocol for incidence of *Mycena* fungus for future studies would allow to further document and understand this relationship.

Other research areas that would lead to a better characterization of the role of shade trees, would be a) the effect of banana (Musa) trees, due to evidence on their potential as shade trees for coffee (van Asten *et al.*, 2011) as well as b) measures of weed cover (instead of just litter) also strongly linked to runoff and erosion prevention (Iijima *et al.*, 2003).

### *6.3.2 PAYMENT FOR ECOSYSTEM SERVICES (PES) SCHEME*

In the process of this project we have attempted to quantitatively evaluate potential cropping systems for reducing erosion that farmers can apply. We used CAF2007 and work sessions with farmers to explore options and try and reach optimal solutions when possible – i.e. lowest loss of coffee production for the highest gain in erosion control. However, we also wished to evaluate the suitability of a range of different erosion control practices, in order make recommendation for a potential Payment for Environmental Services (PES) scheme, which the ICE (owners of the hydroelectric dam network in Costa Rica) expressed an interest in (Mendelez, 2010).

While PES schemes can reward time and labor invested in direct erosion control measures such as vegetative barriers, they can also compensate farmers for a loss in production caused by erosion control practices negatively impacting coffee yield. In the case of shade trees, we have yet to acquire additional evidence on annual yield variations as well as effect on Mycena fungus attack in order to measure potential yield loss. The benefits of further investigating this matter are clear: it would provide farmers and the ICE (key stakeholder in erosion reduction) with the elements for negotiating compensations for soil conservation practices. Factors such as risk of climatic variability or fluctuations of coffee price on the global market could also be taken into account.

### *6.3.3 RECOMMENDATIONS FOR EROSION CONTROL MEASURES*

In this part, changes in farming practices are suggested that integrate results in the prototyping process.

In this thesis, the main erosion control practice that was investigated was the use of shade trees for increasing litter and water infiltration rate, and decreasing evapotranspiration rates. We did find positive effects of shade trees on the first two elements. These results were similar to those found by Lin & Richards (2007; Lin, 2010), which found that Erythrina trees helped improve soil water conservation and infiltration, albeit at much higher shade levels. Forthcoming studies using data with runoff and erosion should help precise this relationship. Nevertheless, considering the lack of negative effect of shade trees on coffee production (see Chapter 2) we are inclined to suggest that increasing shade tree density (or increasing canopy by reducing pruning intensity and frequency) could significantly improve soil conservation in these coffee plots. Several farmers expressed interest in attempting this in Chapter 4.

Ataroff & Monasterio's study (1997) concluded that total plot LAI, coffee renovation, and frequency of human interventions in the field were major factors influencing erosion in a coffee plantation in a mountainous area. Other erosion control methods were frequently discussed but could not be modeled nor were they quantitatively measured. Nevertheless, a more precise study on the effect of vegetative barriers, weed cover, and management of pruning residues (versus the cost of each of these activities) would help make more precise recommendations to farmers and cooperative on this point.

Gomez-Delgado *et al* (2011) compared runoff and erosion in two adjacent coffee plots, one with and the other without Erythrina shade. Although there were differences between the two plots, the total amount of erosion was minute compared to the total sediment output in that watershed. This reflects a reality that other landscape features, especially pathways and roads, generate much higher rates of sediment than coffee plots. Large-scale erosion control plans must therefore account for this effect and prioritize their actions adequately. Nevertheless, we note that the aforementioned study was performed in a region characterized by rich andosols presenting in a deep and extremely permeable layer, and low overall levels of erosion; in contrast, Llano Bonito soils had much higher clay content and probably lower absorption rates and higher erosion. The recent installation of a flow and turbidity meter in one of the valley's rivers will generate useful data in the coming years on the amount of sediment production from coffee plantations in the watershed.

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