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The role of canopy structure in leaf litter production, quality and decomposition in rustic and traditional coffee systems and forests in Mexico

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THE ROLE OF CANOPY STRUCTURE IN LEAF LITTER PRODUCTION, QUALITY AND DECOMPOSITION IN RUSTIC AND TRADITIONAL COFFEE SYSTEMS AND FORESTS IN MÉXICO

A thesis submitted by:

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Abstract

Changes in the canopy structure and species composition as part of the agricultural management in traditional and rustic coffee plantations affect the nutrient cycling through the alteration in the litter quality and production deposited in the forest floor. The use of endemic canopy tree species of the subperennial medium forest in the coffee plantations can be an important component for the leaf litter production in terms of quality and quantity and can be as well, important for the nutrient storage, litter decomposition and the general physical-chemical characteristics of the soil.

The objetives of this research was to study the changes in the tree canopy species composition and the effect in the quality of the leaf litter and the effect of it in the decomposition rates of the litter deposited in the forest floor. A study about the contribution and quality of representative species litterfall in traditional (TCS) and rustic coffee systems (RCS) and subperennial medium forest (Spmf) was performed with the objective to analyze the effect of the litter qualities in the forest floor decomposition processes. The study was carried out in the community of San Miguel in the Mountain range of Atoyac in Veracruz, México. Nine plots (20 × 50 m), were randomly established, three in each of traditional (TCS), rustic coffee plantations (RCS) and disturbed sub-perennial medium forest (Spmf). All plot vegetation inventoried and Shannon diversity index (H') and Jaccard similarity index (Jcc) calculated per system. In each plot, four littertraps ($1m^2$) were placed to collect leaf litter from the trees. The leaf-litter collection was carried out every 15 days for 12 months.

Organic matter decomposition process was evaluated using the litterbag method, 252 litterbags were placed in the nine plots and sampling was performed at intervals of: 0, 22, 44, 88, 176 and 352 days. Soil analyses were performed on the same dates and sites of collection of litterbags and included total N, P, K, Ca, pH and organic matter content. Differences in tree canopy species composition and litter production influenced the litter quality deposited on the forest floor and decomposition and nutrient cycling on the systems studied.

Nutrient analyses of the litterbags contents (*Robinsonella mirandae, Coffea arabica, Mastichodendron capirii, Piper hispidum, Croton officinalis* and a representative tree species general mixture per system) were performed at each litterbag collection to determine best quality and predict the changes in the leaf litter quality over time. Analyses were for total N, P, K, Ca, hemicelluloses, celluloses and lignin contents were also determined. The decomposition rate was calculated by developing the "k" constant from the weight loss of the litterbags. Results indicated that litter quality and climate influenced decomposition rates and decomposition probably follows two distinctive phases that ocour with the start of the rainy season and the dry season.

The parameters that most influenced the decomposition process were lignin:N and C:N ratios followed by the initial rates of N and P. Quality species with the highest content of N and the lowest initial lignin:N and C:N ratios were *Robinsonella mirandae/Coffea arabica* in Spmf, *Mastichodendron capirii* and *Piper hispidum* and these showed the highest rates of decomposition which increased continuously with time. Low quality litter represented by *Croton officinalis* had the lowest rates of decomposition and the lowest N, lignin:N and C:N ratios and progressive declines in cellulose and hemicelluloses which were approximately linear over time.

Increasing N and P soil concentration are correlated with S.O.M. at different times of the year, but probably do not have any effect on decomposition rates of litter. In general it was concluded that the changes in the tree canopy species composition does have an effect on the litter quality deposited in the forest floor of coffee plantations and disturbed forest and consequently in the nutrient cycling in the ecosystems.

This thesis is dedicated to my mother: **Amelia Enríquez Chávez** whose unconditional support, love and patience were basic to complete this degree.

Esta tesis esta dedicada a mi madre **Amelia Enríquez Chávez**, por su inagotable paciencia, amor y apoyo durante todo el tiempo de realización de este grado. También agradezco a mi hermana Maricarmen y a Sigfired Bohm por ser el apoyo mayor (después de mi ma') durante estos estudios.

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I am grateful to all my friends from SENR, University of Bangor, Wales, for being the surrogate family during the many years I stayed there and for their continued moral support there after. From the staff, Sheila Jones and Dr. Callahan are especially thanked for their care and attention.

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Rozó con fuego
el altonivel
de los mañios,
el baluarte del roble,
la ciudad del raulí,
la rumorosa colmena de los ulmos,
y ahora desde las raíces quemadas
se va la tierra
nadie la defiende.
[...]
El filo de las hachas
cayó cortando ramas
y levantando vuelos y sonidos!
Ay quién pudiera detener
el curso del río de la leña,
desandar el camino
devolverlo a la selva.

Pablo Neruda

List of abbreviations and symbols

α-cellulose= Alpha-cellulose

$= Mexican peso

£= Stirling pound

°C= Celsius degrees

ADF= Acid detergent fibre analysis

AFS= Agroforestry systems

ANOVA= Analysis of variance

ASERCA= Apoyos y Servicios a la Comercialización Agropecuaria

C:N= Carbon / Nitrogen ratio

^{13}C= Carbon 13

Ca= Calcium

COLPOS= Colegio de Posgraduados en Ciencias Agrícolas

CONABIO= Comisión Nacional para el conocimiento y uso de la Biodiversidad

CONAFOR= Comisión Nacional Forestal

D.b.h.= Diameter at the breast height

E= Eveness

F= Variance ratio

f^3= Cubic foot

FAO=Food and Agriculture Organization

GEO-MEXICO= Geo-referenced Population Data sets of México

G.I.P.= Gross income product

H'= Shannon diversity's index

ha= Hectare

Hcel= Hemicelluloses

HSD test= Homogeneity of variance test (Tuckey)

ICRAF= World Agroforestry Centre

INEGI= Instituto Nacional de Estadística, Geografía e Informática

INIFAP= Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias

INMECAFE= Instituto Mexicano del Café

Jc= Jaccard similarity's index

k= Rate of decomposition

$kg/ha/yr^{-1}$= Kilograms per hectare per year

kg/ha^{-1}= kilogram per hectare

kg= Kilogram

Lignin:N= Lignin / Nitrogen ratio

log= Logarithm

logt= Logarithm base 10

$^{m.s.}$= marginally significant

m= metres

m^3= Cubic metre

ml= milliliters

mm= millimeters

n.d.= Not defined

$^{n.s.}$= Not significant

N= Nitrogen

N= Normality in solution

NDF= Neutral detergent fibre analysis

NPP= Net primary production

P= Phosphorous

P= Probability

Qq= Quintal (100 kgs)

R^2= Coefficient of determination (Regression)

RCA= Rustic coffee system

Rel. B/C= Benefit/Cost relationship

S.O.M.= Soil organic matter

SD= Standard error

Spmf= Subperennial medium forest (semi-evergreen tropical forest)

Spp= Species

TCS= Traditional coffee system

$ton/C/ha^{-1}$= Tonnes of Carbon per hectare

$ton/ha/yr^{-1}$= Tonnes per hectare per year

ton= Tonelades

UNESCO=United Nations Educational, Scientific and Cultural Organization

USDD= United States Department of Defense.

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Chapter 1 General introduction

1.1 Background

The use of the tree canopy of the tropical native forest as a shade in traditional and rustic cacao plantations in México has been practiced since long before the Spanish conquest in America; mainly in México and Guatemala by cultures such as the Aztecs and the Mayans in the meso-American area. The cacao systems were based to a large extent on religious and social beliefs, which continued being practiced by the natives during the 16th and until 19th century when it was adapted to the coffee culture in the area of Veracruz and later in the southern states of México, mainly Oaxaca and Chiapas.

The evolution of the use of the tree shade species for these crops, mainly in coffee, has been done mainly during the 20th century, with the inclusion of more specialized technics and coffee varieties. The use of tropical tree species composition of the canopy has replaced native species of the tropical forest for other species such as *Inga* spp., *Cecropia obtusifolia*, *Gliricidia sepium* and other leguminous trees, beside of some economically valuable woods such as the *Swietenia macrophylla* (Mahogany) and *Juglans* sp. (Walnut), *Cordia alliodora*, *Robinsonella mirandae*, *Dipholis minutiflora* and *Mastichodendron capirii* (Escamilla and Diaz, 2002).

During the decade of 70´s, the state policy on coffee production and commercialization was to replace the native and traditional canopy tree species with leguminous tree species which shade in the traditional commercial and technified coffee plantations, preferred species were *Inga* spp., and *Cecropia obtusifolia* (Martínez, 1988; Moguel and Toledo, 1999), which caused fragmentation of the native vegetation of the zone of neo-tropical vegetation of México and resulted in an overall native species alteration (Faminow and Ariza-Rodríguez, 2001, Hietz, 2005).

Nevertheless, the management of coffee and cacao crops has been more recently diversified mainly due to two causes, the socio-economic circumstance of the farmers and the multipurpose use of the forest tree canopy species in these zones (Escamilla, 1995, 1997). Five typologies of coffee systems with varied canopy use have been

proposed (Escamilla, 1993; Moguel and Toledo, 1999): 1. Rustic or Mountain coffee system (RCS), in which the canopy of the disturbed tropical forest is used, and a high percent of native species are still present as part of the canopy; 2. Traditional coffee system (TCS), which resembles a home garden; 3. Traditional commercial coffee system, which uses exotic species such as citrus and other fruits as well as woody trees for shade, 4. Specialized coffee system, which uses only a few species as shade (*Inga* spp., *Cecropia obtusifolia*, *Cedrela odorata* and others timber species), 5. Open to sun or unshedded monoculture.

The use of shade trees in the canopy of the rustic and traditional coffee plantations is basic for the functioning and development of the agro-ecosystem, supporting functions such as nutrient cycling, nutrient stock and sustainability of all the other life forms inside the system. In the case of the traditional and rustic coffee plantations, litterfall quality determines many other processes of basic importance in the forest floor such as soil nutrient cycling and mineral nutrient availability. Some important relationships rely on the biodiversity and organic matter decomposition processes which can be essential for the functioning of nutrient cycling in the system.

1.2 Justification of the project

The importance of tree diversity and their litter contribution to nutrient cycling in rustic and traditional coffee systems has not been widely documented. The study of modified natural systems such as the traditional and rustic coffee plantations that differ in canopy tree diversity, composition and litterfall production, can be important for the study of the litter quality and influence on decomposition processes and nutrient turnover in the tropical ecosystems.

1.3 Hypothesis

The importance of litterfall contribution of the tree species diversity in the canopy of native forests and coffee plantations is a determining factor in the processes of decomposition of organic matter and availability of nutrients in these systems. Where the canopy of natural system is altered it is expected to affect the processes involved

in leaf litter production, quality, rates of decomposition and finally on the nutrient recycling and availability for plants.

Litterfall quality contributed by the native dominant species in the canopy of traditional coffee systems is fundamental in the mantainance of the sustainability of the nutrient cycling of the system, besides the colonies of decomposer organisms and the physical-chemical environmental conditions and climate (Aerts, 1997). The diversity and composition of perennial and deciduous tree species are complementary mixtures necessary to maintain the sustainability of the system by providing a balanced nutrient contribution through the litterfall quality.

1.4 General objective

To study the influence of the production and quality of the litter of canopy native trees in the decomposition process and nutrient turnover in traditional and rustic coffee systems and to compare with those of subperennial medium forest

1.5 Specific objectives

*To perform a species composition and agroforestry characterization of RCS and TCS;
*To identify the dominant native tree species of the canopy (RCS) and (TCS) coffee systems as well in perturbed subperennial medium forest (Spmf) and their contribution to leaf litter production;
*To study litter quality of the dominant canopy species in RCS and TCS and changes in quality over time;
*To study litterfall quality parameters such as N, P, K and Ca, as well as hemicelluloses, cellulose and lignin and their influence on decomposition rates;
*To analyze the influence of soil and decomposer micro-organisms on decomposition processes in relation to the leaf-litter quality
*Finally to analyse the correlation between the parameters studied and their effect on decomposition processes.

Chapter 2 Literature review

2.1 Forests in the world and México.

Deforestation in tropical zones is not only of ecological concern, but it is also an indicator of other social, economical and political factors, which equally affect the land patterns, forest resources and vegetation cover. Natural forests are being globally reduced at an accelerated annual rate of 13.1 million of ha per year, of which the 10 richest countries account for two thirds of the total forest area lost (FAO, 2007). This is due among other factors to deforestation, growth of the agricultural border in tropical zones, fragmentation of forests, demographic growth and the climatic global change effects that have generated other type of disturbance such as the occurence of the climatic phenomenon of El Niño. The elimination, exploitation and modification of the native vegetation have resulted in extensive and irreversible change in most forests and jungles of the world, contributing to the problem of global warming due to greenhouse gas production.

México have a total area of 195,820,000 ha of it 109,072,000 ha was calculated as original forest cover, but only 2,364,000 ha (1.2 %) are considered to remain as intact forest landscape (INEGI, 2009). Sánchez-Colon et al. (2008) estimated that around 484,000 ha per year are lost annually, less than 615,000 ha per year calculated by Masera (1996) and of those around 470,000 ha are of tropical forest.

Table 2.1 Changes in the forest cover in México (1990, 2000 and 2005).

Forest type	1990		2000		2005	
	(1000 ha)	%	(1000 ha)	%	(1000 ha)	%
Primary forest	38,775	19.8	34,825	17.8	32,850	16.8
Natural forest	(n.d.)	(n.d.)	64,482	32.9	63,180	32.3
All forest	69,016	35.2	65,540	33.5	64,238	32.8
Rate of annual change*	1990-2000			2000-2005		
	-348,000 ha	-0.5 %		-260,000	-0.4 %	

Source: United Nations Food and Agriculture Organization (FAO), 2007.

*Source: http://www.fao.org/forestry/static/data/fra2005/global_tables/'4'!A1 (2006).

The most important changes in the vegetation cover and land use in Mexico are because the human activities as agriculture and cattle, which form part of the economic activities in tropical zones. Semarnat (2009) compiled data about the changes because of these activities and how it affects the total area of forests and arid zones as it shows as follows (Table 2.1).

Table 2.2. Forest cover variation in Mexico (1993-2000).

Land use	1993 (Ha)	2000 (Ha)	Variation Area (Ha)	*Percentage (%)*
Agriculture Total	30,198.400	32,803.781	2,605.381	*8.63*
Temperate forest	34,666.107	32,851.306	-1,814.801	*5.24*
Tropical forest	34,387.491	30,816.633	-3,570.858	*10.38*
Cattle	27,791.854	31,787.163	3.995.309	*14.38*
Arid zones bushes	57,959.607	55,810.305	-2,149.302	*3.71*
Other	8,886.659	9,820.930	934,271	*10.51*
Total	*193,890.118*	*193,890.118*	*0*	*0*

Source: SEMARNAT. Conafor. Anexo estadistico. (http://www.conafor.gob.mx (2009).

2.1.1 Forests in Veracruz, México.

The tropical and temperate forests of Veracruz occupy 1.9 million hectares, 26% of the territory. Only 15,447 hectares are under some type of management, which is 0.89% of vegetation surface cover.

The authorized annual logable volume is 150,000 m^3, but the illegal wood commerce is an additional 150,000 m^3. There are 80 registered industries with the capacity to log 293,000 m^3. The consumption of firewood for fuel is extremely high, about 2 million m^3 per year. Veracruz is one of the states with greatest forest destruction, and is thought to have lost 70% of its original natural wealth. Official data estimates are that until 2005, every year 2,800 ha per year are deforested. Annually, 178 forest fires are registered, with an affected surface area of 1,746 hectares. The contribution of the forest economic activity to the state gross income product (GIP) is 0.3 %, occupying ninth place in national forest production. The state has about 1.5 million potential hectares to establish forest commercial plantations (woody and non woody) (Inifap, 2005; Conafor, 2006 http://conafor.gob.mx/regiones_conafor/zona10.htlm).

Dirzo and García (1992), showed rain forests losses in the Tuxtlas region in México over 20 years from 1967 to 1987. The deforestation progressed from the lowlands and by 1986 about the 84% of the original forest had been lost. It was predicted by the same researchers that by the year 2000 only 8.7 percent of the original forest would remain in the form of an archipelago of small islands of forest fragments. Deforestation in this area is caused mostly by clearance for cattle production, fuelled by human population growth of more than double in the last 25 years (Krebs, 1994).

A study in tropical forest vegetation in the mountain range of the Tuxtlas, in Veracruz was done by Guevara et al. (2004). This study included the period from 1972 to the 1993, which, was divided in three intervals: from 1972 to 1986, from 1986 to 1990 and from 1990 to 1993. In this study, in 1972 the Tuxtlas was composed of 97.015 ha of tropical and temperate forest, and at the end of the period of study (1993) it remained only 54.281 ha equivalent to 56% of the initial forest cover.

The rate of annual deforestation was of 1.89% between 1972 and 1986, 1.10% from 1986 to 1990 and later increased to 9.42% in the last period from 1990 to 1993. Finally, the last study done during 2004 and 2005 showed that the rate of deforestation in the Reserve of the Biosphere of the Tuxtlas was of 1.73%, although this study in fact is of only six months because the used satellite photos were from November of 2004 to April of 2005 (CONANP, 2006).

Some of the main forestry species planted are the most valuable timber trees: *Cedrela odorata* (Cedro), *Swietenia macrophylla* (Mahogany), *Tabebuia rosea*, *Roseodendron donell-smithii* (Primavera) and *Cordia alliodora* (Xochicuahuitl); and the exotic species: *Tectona grandis* (Teca) and *Gmelina arborea*; Temperate species such as Pine (*Pinus patula, Pinus chiapensis, Pinus pseudostrobus, Pinus ayacahuite* and *Pinus montezumae*) and *Abies religiosa* (Oyamel), *Cupressus lindleyii* (Cypress), *Liquidambar macrophylla* (Liquidámbar) and *Quercus* spp (Oak) are of less importance.

2.1.2 Biodiversity (Flora and Fauna)

México is considered as one of countries with greatest biological diversity in the American continent. The confluence of the two biological regions, the Neartic and Neotropical contribute to enhanced biodiversity as well as the topographic extremes characterised by four mountain ranges, the Sierra Madre Occidental, Sierra Madre Oriental, Sierra Madre del Sur and the Neovolcanic Axis (Mittermier and Mittermier, 1997).

México occupies 5th place world-wide in vascular plants, with 23,522 species and esteem that the number could approach 31,000 and a important diversity in beans, corn and pine species as well. The states with the higest species diversity are Michoacán, Guerrero, Oaxaca, Veracruz and Chiapas which have the greater plant diversity with 8,248 registered species, and have the 35% of the total vertebrates of México (INEGI, 2009).

It occupies the second place in the world by the variety of species of reptiles, with 804 of the 8,240 well-known species; the third in diversity of mammals, with 530 of the 5,130 existing species; and third as well in number of amphibians, with 361 of the 6,035 classified species. In birds it occupies the twelfth place, with 1,107 of the 9,721 species known in the planet (INEGI, 2009).

Table 2.3. Fungus, Plant and Animal species diversity in the world and México

Group	World known species	México known species	Percentage (%)	México steemed species
Insects	933 000	77 307	8,28	425 000
Vascular plants	270 000	23 522	8,71	31 100
Other arthropods	115 000	10 000	8,69	75 000
Other invertebrate	100 000	15 000	15	23 846
Fungi	72 000	6 000	8,33	7 200
Seaweed	36 000	2 702	7,5	3 600
Fish	27 977	2 200	7,86	2 420

Group	World known species	México known species	Percentage	México steemed species
Mosses	12 800	1 480	11,56	2 000
Birds	9 721	1 107	11,38	1 167
Reptiles	8 240	804	9,75	812
Amphibians	6 035	361	5,98	671
Mammals	5 130	530	10,33	600

Source: **CONABIO.** 2009. Capital Natural y Bienestar Social (http://www.inegi.org.mx/inegi/contenidos/espanol/prensa/contenidos/estadisticas/2009/ambiente0.doc)

Amongst current assessments of México biodiversity is considered to be within the 10 more diverse areas of the planet along with Brazil, Indonesia, India and Madagascar (Ramamoorthy et al., 1993), which between them contain up to 70 % of the total of known species (Mittermeier & Goesttsch, 1992). México's rain and temperate forests contain only around 1% of the surface of the planet, but are habitat for around one tenth of all terrestrial vertebrates and plants known to science (Barton-Bray et al., 2003). In the south-east of México, the states of Chiapas and Oaxaca are primary considered as the areas of greatest biological diversity, with respect to vascular plants 26,000 species have been identified, with approximately 1,384 in Veracruz State, 56 of which are in danger of extinction and 168 endemics are threatened (Vovides, 1981; INEGI, 1998). The regions of the state of Veracruz that are considered as critical because of rates of deforestation are: Los Tuxtlas, Uxpanapa, the mountain range of Zongolica, Cofre de Perote, Orizaba and Misantla (Toledo and Ordoñez, 1993; INEGI, 1998).

2.2 Agroforestry systems (AFS)

Agroforestry had been practiced in the American continent by ancient cultures such as the Aztec and Mayan civilizations centuries ago, some examples are the productive "home-gardens" in the Olmecan and Mayan cultures or the "Chinampas" systems by the Aztecs and cacao cultivation in central and south-east México by the Mayan society. These agroforestry systems (AFS) in the American continent always had some characteristics that linked the religious beliefs with the environment and the production of goods such as wood and fruits. Today these systems have changed and

adapted to include other exotic species such as *Mangifera indica, Citrus spp* and *Coffea arabica* amongst others. The traditional coffee and cacao systems are widely practiced in the states of Veracruz, Oaxaca and Chiapas and Tabasco, in which the conservation of the tree canopy of the tropical forest is used as cover to provide with shade to the coffee or cacao (Escamilla, 1997; Santoyo et al., 1994).

The canopy also has an important role in production diversification with commercial wood, fuels, fruits, medicinal and ornamental species growing all together in the same space and time. These AFS in the tropical zones contribute to create the conditions for the practice of sustainable agriculture (Budowski, 1992).

Agroforestry is a relatively new name for ancestral agricultural practices in many cases and which is in constant development. Different definitions have been developed, one of most complete is by Sinclair in 1999 (Schroth and Sinclair, 2003): "Agroforestry is a set of land use practices that involve the deliberate combination of woody perennials including trees, shrubs, palms and bamboos with agricultural crops and/or animals on the same land management unit in some form of spatial arrangement or temporal sequence such that there are significant ecological and economic interactions among the woody and non woody components"

Another definition for agroforestry proposed by the World Agroforestry Center (ICRAF, 2000) says: "Is a dynamic ecologically based natural resource management practice that through the integration of trees and other tall woody plants on farms and agricultural landscape, diversifies the production for increased social, economic, and environmental benefits" (Schroth et al., 2004). So then, we have a system which the main components are trees that can be used with other components such as shrubs, plants, animals and even fish or insects, this definition implies that:

a). - Agroforestry normally is incumbent on two or more species of plants (or plants and animals), in which at least one of these is a ligneous perennial species;
b). - An agroforestry system always has two or more outputs (exits),
c). - The cycle of an agroforestry system is always greater than a year;
d). -Even the simpler agroforestry system, is more complex economically and ecologically (structural and functionally) than a monoculture system.

AFS focus on the ecological and socio-economic aspects of a specific zone of study and through its analysis its potential can be determined. Structurally it is a physical design of crops in the space or through time and functionally it is the unit that processes diverse sources of income from light, nutrients, water, into output products in the form of food, fibres, firewood, etc. (Nair, 1997), AFS also can be of a farming type while includes animals and displays the attributes of any system; limits, components, inputs and products, component interactions, a hierarchic organization and energy flow dynamics within the parcel (Montagnini, 1992). Other services from the systems include soil nutrient cycling, carbon sequestration (Andrade et al., 2008) soil conservation (Young, 1990) and biodiversity among others.

The AFS are dynamic, because the conditions of their components and their components themselves change through time. Some features demonstrated in agroforestry systems hydrological cycle are the diminution of the evapo-transpiration rate of the shaded crop the and the removal of the excesses of humidity in the soil by means of transpiration from a dense tree vegetal cover; for example in tea plantations in the northwest of India (Phatak et al., 1993).

An increase in humidity has been recorded by means of horizontal interception of fog or clouds in zones with tropical forests; for example with *Grevillea robusta* in tea plantations in Tanzania (Rocheleau and Weber, 1988). Thus AFS can be considered as one of the alternatives best adapted for management and conservation of natural resources, taking into account their biological, ecological and socio-economical characteristics and can help to enhance the biodiversity of birds and insects between others (McAdam et al., 2007). These functions are based on the relation between the diverse existing species within the system with respect to the crops, animals (cattle or other type of management) and including insects and fish.

2.2.1 Structural basis for classification in Agroforestry Systems (AFS)

AFS can be defined in terms of the components and the function of these in terms of products or services as well as for the arrangement or disposition in time and space. Some of the criteria that can be used to classify a AFS are a) structural criteria, which refers to the composition of the system elements, including the spatial mix of the

woody elements, the vertical stratification and the temporal nature and arrangement of all the components of the system; b) functional criteria, refers to the principal function of the woody elements of the system (producing for example fuel, wood or providing protection as wind break barriers, belt protection or ecological spread as soil conservation) and, c) socio-economical criteria, inputs and outputs referring to the economical and social importance of the woody components of the system (Budowski, 1992).

These three criteria are related to each other and are not exclusive, the direct interrelation among them because of their structural and functional bases are related to the ligneous components in the system, whereas the socio-economic stratification is refered to the organization of the systems according with certain defined conditions which are part of a defined specific structure (composition and arrengement of its elements) and with function.

2.2.1.1 Nature of components

Three basic components are part of the AFS and managed by human beings: Trees (woody perennials), plants and herbs (including crops and pastures) and finally animals. Some exceptions are other specific systems such as apiculture and pisciculture with trees and with these elements is made the most simple classification for AFS (MacDicken and Vergara, 1990):

Agrisilvicultural: This involves trees, including shrubs and/or vines
Silvopastoral: Pasture and/or animals and trees; and
Agrosilvopastoral: Crops, pastures and/or animals, and trees (Nair, 1997).

Some of these systems have been widely practiced in the past ancient cultures in Asian and American continents as did the Mayan and Aztec cultures (with Home gardens and Chinampas), the Incas and the Taungya system in south East Asia to name some examples (Krishnamurthy and Avila, 2001).

2.2.1.2 Arrangement of components

This refers to the arrangement of the components in the system in both space and time. In some cases the arrangement of components of trees and plants can form a mixed and dense stand, as happens in some home gardens, or can be spread over the same land area when the trees are mixed with pastures and animals. There are several ways to mix all these components over the space as in rows, strips, alternate blocks in smaller spaces and alternate blocks in macro zonal spaces.

The temporal arrangements can be short or long term, depending on the life cycle of the trees, plants or animals, and these components can be managed in different ways to allow them to regenerate in a natural way by planting / sowing depending on the nature of the component. In some cases it can involve a shifting cultivation cycle or rotation (as with pastures) over several years. These temporal arregements can be described as coincident, concommitant, overlapping, separate or interpolated (Huxley, 1983; Vergara, 1982; Torquebiau, 1990).

2.2.2 Characteristics of the agroforestry systems (AFS)

Two of the most important and intrinsic concepts to all agroforestry systems (AFS) are those of *sustainability* and *productivity* (King, 1987). An AFS is *sustainable* when deterioration of the productive capacity does not take place, as can happen in agricultural systems, where the increase of erosion and the diminution of soil fertility are two consequences of this type of production management (Panjab-Singh and Phatak, 1994).

According to Torquebiau (1990), the main requirements of sustainable agriculture are:
- The conservation of the soil, including the control of the erosion and the maintenance of the humidity;
- The use and conservation of the existing resources of soil, water, light, energy, genetic resources and labour;
- The use of biological interactions between different elements of the system, this can be the association of climbing plants and supports, nitrogen fixation and the biological control of weeds and diseases; and

- The use of easily available inputs and practices that can assure the health and conservation of the environment.

2.2.2.1 Trees in association with perennial crops

In agreement with Montagnini (1992), this category of AFS forms the commercial exploitation systems of coconut palms, rubber or palm in association with other crops like coffee and cacao, including woody and non woody trees. In the cases of cacao and coffee crops, the trees constitute the base for many simultaneous systems (Licona et al., 1995; Beer and Somarriba, 1999). In most of the tropical regions where the traditional coffee system is cultivated (as happens in Africa and Latin America) it is considered as a multistrata system, where a diversity of trees with multiple purposes provides the function of shade for the crop (Raintree, 1989).

The presence of trees in the agricultural production systems contributes to recreation of favorable conditions for their sustainability and productivity (Gordon and Bentley, 1990). These conditions influence the cycling of nutrients, provide protection against soil erosion, modification of the microclimate (Jha, 1994), and effects the populations of plagues among others (Haggar and Staver, 2001; Staver, 2001; Guharay et al., 2001). The processes that occour in the tropical forests help us to understand better the processes that happens within the AFS, in this type of forests, mainly those in areas of high precipitation, it is considered that the majority of nutrients are in the living vegetation and in that way are conserved from leaching and soil erosion (Jordan, 1985; Montagnini and Jordan, 2005).

2.2.3 Coffee in agroforestry systems

Coffee is one of the agricultural crops of greatest importance in the world; it is produced in more than 50 countries which are mainly located mainly between the tropics of Cancer and Capricorn. Main coffee producing countries (by volume) are: Brazil, Colombia, Vietnam, Indonesia and México (ASERCA, 2002). In the east of Africa is cultivated in high fertility soil, where it is part of a multishade system of woody trees such as *Albizia* sp and *Grevillea* sp., which provide shade to the coffee crop and probably to other annual crops like beans (Rocheleau and Weber, 1988).

In Guatemala, this same system of *Grevillea* sp., produces small boards and wood used to build floors in houses. Other shade coffee systems with diverse trees in Costa Rica provides other type of products and services like *Erythrina poeppigiana*, fruit trees like *Musa* spp., *Citrus* spp., and *Mangifera* sp., which can have more uses as shade, food, medicinal, nitrogen fixation, aesthetical and other wood or fuel (Lagermann and Heuveldop, 1983).

These traditional systems are mainly practiced in tropical zones in which are grown cacao and coffee plantations. In these systems a great diversity of species are used and like the systems previously described, these include fruit, woody and multipurpose trees (Escamilla et al., 1994; Licona et al., 1995). The rustic and traditional coffee systems are a compound of mainly native representative species of the dominant vegetation in the zone, which they share in time and the space. One of the characteristics in these systems are the null use of agrochemicals such as fertilizers, fungicides and pesticides and they are not mechanized either.

2.3 Coffee in México

Coffee was introduced since 1796 to the region of Córdoba, Veracruz, by Juan Antonio Gómez (Regalado, 1996), 1846 plants of coffee were introduced to the state of Chiapas expanding the crop afterwards to other states. The first export of coffee was in 1803, but it was not until 1882 that México became a coffee exporting country (Nolasco, 1985). Coffee is one of the main agricultural products of México, representing one of the agricultural economic bases for the country and takes place in twelve producing states with an approximate national total surface of 690,000 ha. Veracruz is the second state contributing 25.21% of the national production, just underneath Chiapas and above Puebla and Oaxaca. These four states contribute between 86 and 90% of the national production (ASERCA, 2002).

In Veracruz coffee is cultivated over an area of 152,457 ha; with an annual average yield of 11 qq/ha (quintal equals to 100 kg). The state central zone constitutes approximately 85% of the coffee production surface since have optimal agro-ecological characteristics for the coffee crop. The main producing municipalities are Coatepec, Córdoba, Huatusco, Atoyac and Tezonapa (INEGI, 2005).

2.3.1 Ecology of the coffee plants

Some of the most important environmental elements which define optimal zones for coffee production are rain, intensity of solar radiation and temperature which are directly related to altitude and latitude that altogether determine the productivity and quality of the coffee. Some environmental characteristic elements for coffee plants according to Regalado (1996) and Villaseñor (1987) are as follows:

***Altitude**: From sea level to 1,500 metres above the sea level, although the greatest proportion of the crop is located over 700 m, which together with the factors of low luminosity, fresh temperatures and effects of altitude, favours the growth, fruition and quality of coffee (Villaseñor, 1987). The altitude is classified low until 600 m, medium from 601 to 900 m and high altitude when more than 900 m.

***Temperatures**: Maximum average from 21.3 to 30.6 °C
Minimum average between 10 and 19.9 °C
Mean average between 17.5 and 25.3 °C

***Precipitation**: Maximum annual average 5,075 mm
Minimum annual average 1,077 mm
Mean annual average 2,280 mm (national)

***Effective sun light:** From 1,794 to 1,893 hrs per year which is equivalent to 4.9 and 5.2 hours daily in Chiapas and Veracruz, respectively.

***Soil:** In most coffee zones, as in the centre of Veracruz, the predominant soil origin is volcanic. The best soils for the development of coffee plantations are the deep ones, with good drainage and suitable aeration. The coffee plant requires mainly acid soils. In the Mexican coffee plantation areas the following types of soils are present according to the classification elaborated by the FAO (Villaseñor, 1987) and INEGI (1997): Luvisoles, Rendzinas, Regosoles, Vertisoles, Fluvisoles, Andosoles and Litosoles.

2.3.2 Coffee commercial varieties

The *Coffea* genus belongs to the Rubiaceae family and includes around 40 species, 19 of which have an economic importance (Haarer, 1982). The main species in México are *Coffea arabica* and *Coffea canephora*, which are those of greatest economic interest. *Coffea arabica* is the one of most importance because of its grain quality as much in both national and international scope, as well as by its territorial representativeness. It is estimated that *Coffea canephora* or Robusta as is also called, occupies no more than 2% of the total area cultivated. Some of the most popular varieties are Typica, Bourbón, Caturra, Mundo novo, Garnica, Catuai, Catimor, Maragogype and Robusta (Regalado, 1996). The coffee systems that excel in the Cordoba area and Sierra de Atoyac are mainly the traditional multi-crop and rustic systems.

2.3.3 Canopy structure in coffee systems

The canopy of trees, besides providing shade to the crops, fulfill other functions such as being the structural support of the habitat for a great number of species of animals, plants, insects and microorganisms, all important components for nutrient cycling and health of the system (Beer, 1983). The canopy is composed by the tree component, and all the plant and biotic components that grow on it as ephyfites, parasites, and other plants that grow in the branches and bark of the trees.

The trees play important roles which define their importance in the productive development of the systems that can be considered in the following way (Nair, 1989, 1997): Additions to the soil in the form of organic matter, nitrogen fixation, carbon sequestration and fixation (Cairns and Meganck, 1994), uptake or liberation of nutrients that are in the deepest layers of the soil (not entirely demonstrated); reduction of erosion and protecting against the loss of organic matter through the vegetal cover, reducing erosion factors such as the effects of the sun, rain and winds; effects on the physical properties of the soil by maintaining or improving the structure, porosity and retention of humidity; and effects on the soil chemical properties by means of the reduction of the acidity or salinity.

The presence of trees in agroforestry systems also can have negative effects such as loss of organic matter with harvest, competition for water and nutrients between trees and crops and the presence of allelopathic substances that can be detrimental for the other components and in some cases as in the practice of hedgerows or alley cropping, it may prevent the erosion but may not maintain the soil fertility in high crop yields (McDonald et al., 2002).

For Somarriba (2004), there is a continuum from a very simple to a very complex structure in coffee systems, and they distinguished the following:
*Open sun monocultures (with no shade canopy);

*Coffee plantations with lateral linear tree plantingsin field borders and along roads;

*Monolayered shade canopies (usually with only one shade species);

*Two layered shade canopies;

*Multistorey coffee polycultures with three or more canopy species and with three or more vertical strata, and finally;

*Rustic coffee plantations in which the understory of the natural forest is cleared to plant the coffee bushes, this system is rich in tree species diversity and has a structure similar to the natural forest, with the lowest yield of all the systems already described.

According to the origin, type and use of the tree canopy shade in coffee systems, Nolasco (1985), identified three production systems, with variations by the development degree of development, with a native, semi-native and specialized canopy. This classification was modified later by Moguel & Toledo (1999) and Escamilla et al. (1994), characterizing five different systems: rustic or "mountain" system, traditional polyculture, commercial polyculture, shaded monoculture and unshaded monoculture composed of only coffee plants (Fig. 2.1). These coffee systems are distributed in the centre of Veracruz in the following percentages: specialized 54.3%, traditional policultive 31.5%, commercial policultive 12.2%, and the rustic and unshaded monoculture the remaining 2% (ASERCA, 2002).

The production of coffee in México was initiated under the rustic coffee system around 200 years ago, but at the present time has been almost totally displaced. The rustic system is also known as "traditional or mountain" because the shade composes a great diversity of native tree species of the tropical forest vegetation. Other characteristics are the use of the Typica and Robusta varieties, plantations of over 30 years of age, and suffering from a lack of agicultural practices such as shade regulation, fertilization and sanitary plant control. Limited activities in the plantations as weed control and occasionally some pruning. Under these conditions the yield average is under 6 to 8 qq per ha (Escamilla, 1997).

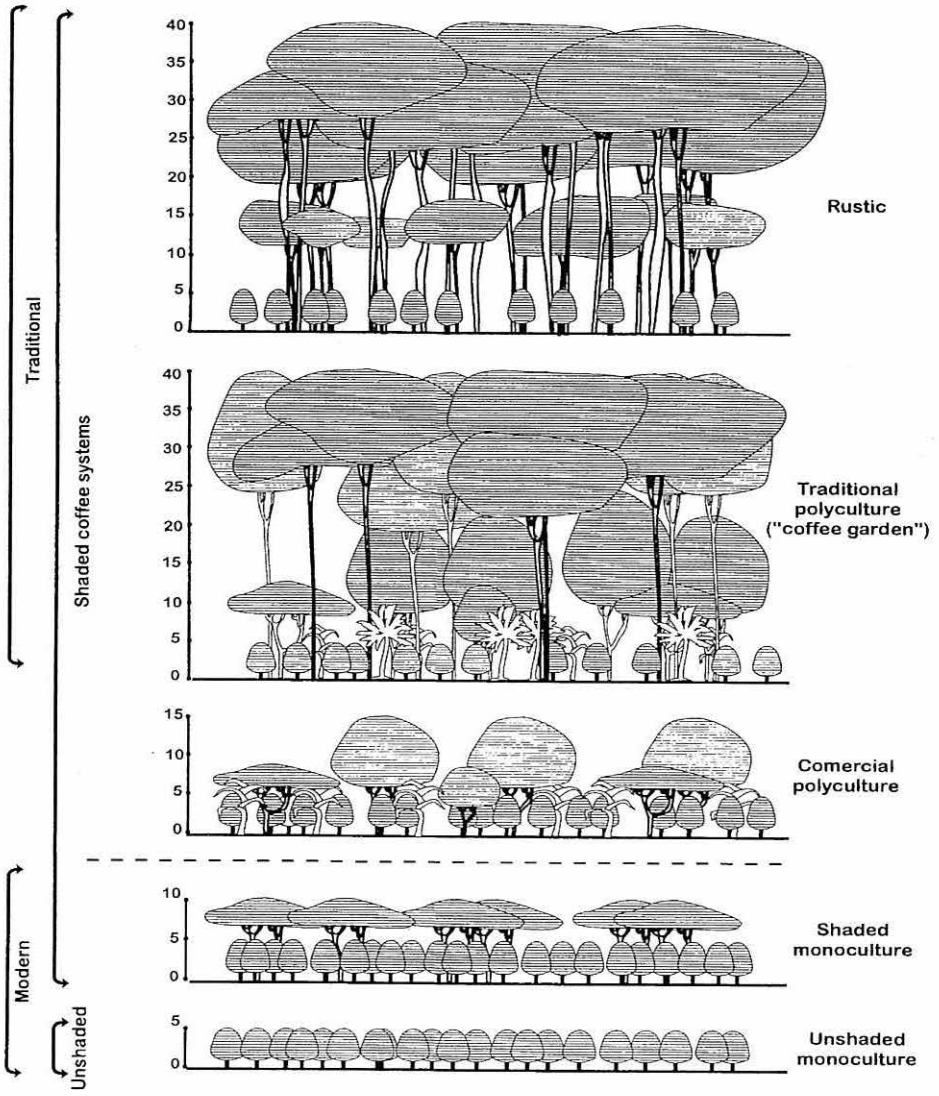


Fig 2.1 Coffee production systems in México.

Source: Moguel and Toledo (1999).

The main difference between the RCS and TCS is the canopy species diversity, having a greater number in the rustic system than the traditional and probably the use of other exotic species such as bananas and fruit trees (*Citrus spp.*, and *Mangifera indica.*) in the traditional system. In México, *Inga* spp and *Cecropia obtusifolia* have been the principal tree species used in traditional and specialized coffee plantations as shade as it was the recommended species during the 70's as part of the government policy for coffee plantations in México (Marten and Sancholuz, 1981).

The traditional and rustic coffee systems are those with greatest biological diversity, although they are of lower productivity in comparison with the other systems; the commercial polyculture is the one of greatest economic productivity, whereas highest yields are obtained in the specialized systems and unshaded coffee, but these are considered of low stability and sustainability (Escamilla, 1993; Harrington, 1996). In México, the specialized system recommended by the INMECAFE had a considerable increment on productivity, nevertheless, the elimination of the native vegetation cover and the use of just a few species for shade reduced the species diversity and ecological sustainability of these systems (Escamilla et al., 1994).

The rustic coffee system has the following particular benefits (ASERCA, 2002, Beer et al., 2003):

*Environmental - protection and conservation of forest species and animals,

*Protection against soil erosion;

*An important role in the reduction of the greenhouse effect;

*Products of organic origin and no agrochemicals used in the production process. The coffee beans mature more slowly, allowing them to gather a higher sugar concentration and contributing to a better and smoother flavour;

*Economically it is more viable in the long term than the intensive crop systems with the product diversification incentives, and one other benefit is the conservation of soil micro-organisms and insects involved in the decomposition processes (Faminow and Ariza-Rodríguez, 2001; Haggar and Staver, 2001; Hairiah et al., 2006).

2.3.4 Leaf litter production

Net Primary Production (NPP) is one of the main processes in terrestrial ecosystems providing the link between organic decomposition and primary production. It is as well the most important route of transfer of energy within the ecosystem (Alvarez-Sánchez and Guevara, 1993) and it is also the main route for nutrient cycling and re-cycling to the soil (Meentemeyer et al., 1982).

In general litterfall production is controlled by physical-biological factors such as soil (Swift et al., 1979) climatic factors (Kumar and Deepu, 1992; Liu et al., 2003a; Lawrence, 2005), temperature and rain (Aerts, 1997; De Dato et al., 2008), chemical interactions with allelopathic substances (Rice, 1984), and growth inhibition through obstruction of light (Vázquez-Yañes et al., 1990) and by soil erosion control (Montagnini et al., 1993). Leaf-litter production can depend as well on factors such as tree age, species and phenological stage (Zimmer, 2002), so all these conditions can create different patterns as part of an environmental mosaic, creating a multitude of different niches that facilitate the regeneration of diverse species and therefore, increases the diversity of the ecosystem.

The importance of litterfall in nutrient cycling and the accumulation of soil organic matter have been widely documented in different ecosystems (Jorgensen and Wells, 1986; Vogt et al., 1986; Lugo, 2006). In addition to the direct precipitation and cortical flows (Cantu-Silva and González, 2001), litterfall is the main source of natural fertilization.

More than half of the annual nutrient absorption in the forest is due to the recycling of litter to the soil and the subsequent recycling of these nutrients represents the main mineral source available (Brown and Lugo, 1984; Stanley and Montagnini, 1999). Additionally, litter deposition to the soil is very important since it produces a layer of organic residues on the soil surface, which through its decomposition by the activity of micro-organisms and environmental factors, will have an effect on the soil physical and chemical properties and consequently will determine the potential of the species to improve the quality of the fertility of the ground and productivity in an ecosystem (Facelli and Pickett, 1991; Del Valle –Arango, 2003; Semwal et al., 2003).

The annual gain of energy and matter by the plant subsystem (the Net Primary Production (NPP) may be distributed in the following ways:

1)- Stored in perennial tissues and as a contribution to the net growth or biomass increase. In forests it may constitute 20-60% of the NPP;

2)- A minor quantity of the NPP is consumed by herbivorous animals feeding on leaves, steams and roots, not exceeding 10 % in forest ecosystems:

3)- In all mature ecosystems the bulk of the NPP is shed as plant litter or is secreted as soluble organic matter. The faeces and carcasses of insects and animals contributes too to the detritus input to decomposition.

The maintenance of primary production is dependent on the replenishment of this pool of available nutrients to balance the uptake taken by the plants. The net primary productivity (NPP) of an ecosystem is defined as the amount of accumulated organic material, that is Gross Primary Production PPN = production - respiration. The productivity values that have been observed in temperate forests approximately represent 60% of the values obtained in the tropical rain forest. The values of PPN also are smaller in the subperennial tropical forest than in the rain forests (8 and 10 ton/ha/yr respectively). The recorded values do not include root production (Jordan, 1985).

Table 2.4 Net primary production in terrestrial ecosystems

Ecosystem	*Net primary production (kg/ha/yr)*	
	Normal range	*Average*
Tropical rain forest	10,000 – 35,000	22,000
Semi-deciduous forest	10,000 – 25,000	16,000
Temperate forest		
Evergreen	6,000 – 25,000	13,000
Deciduous	6,000 – 25,000	12,000
Boreal Forest	4,000 – 20,000	8,000
Savanna	2,000 – 20,000	9,000
Temperate pasture	2,000 – 15,000	6,000

Source: Examples of the total biomass of some tropical forests (adapted of Vogt et al., 1996)

2.4 The decomposition system

In ecosystem functioning there exist three related different subsystems (Swift et al., 1979), the plant subsystem, the herbivore subsystem and the decomposition subsystem. Within the ecosystem the decomposition subsystem performs two major functions: The mineralization of essential elements and the formation of soil organic matter, both are necessary to maintain plant production.

Mineralization is the conversion of an element from organic to inorganic state. This includes for instance the formation of CO_2 as a result of the respiration of carbohydrates and the formation of ammonia from protein degradation. The residue of decomposition contributes to the formation of the soil organic matter (SOM). The cellular fraction is the component of the soil organic matter which is the particulate matter formed by the action of decomposers organisms.

2.4.1 The organic matter decomposition process

Decomposition of plant litter refers to the physical and chemical processes involved in reducing litter to its elemental and basic chemical constituents and are determinants of nutrient cycling in most terrestrial ecosystems. Aerts (1997), states that this is a triangular process which involves the following as main factors: climate or physical-chemical environmental factors (Swift et al, 1979); quality of the resource and colonies of decomposer organisms. These factors can actually be part of a hierarchical order, controlling the decomposition rates in the soil. For the early stages of decomposition the climate and concentrations of soluble nutrients in water and structural carbohydrates in leaf-litter are strongly related, whereas the later stages of decomposition are influenced by the lignin concentration (Berg, 2000). The mass loss vs time, is almost always greater for litterfall in environments with higher nutrient availability, but this is reduced with an increase in lignin or polyphenol concentrations (Preston and Trofymow, 2000).

For tropical ecosystems, research conducted on decomposition of organic matter indicates that the factor with most influence for these processes is the quality of the resource (Meetenmeyer, 1978; Swift et al., 1979; Couteaux et al, 1995; Aerts, 1997;

Hoorens et al., 2003), but also others such as temperature, moisture (Berg, 2000), soil nutrient status (Verhoeven and Toth, 1995) and soil fauna (Van Veen and Kuikman, 1990; Kominoski et al., 2009) points that factors such as the colonies of microorganisms and the physical-chemical environmental conditions can be important as well (Aerts, 1997; Sariyildiz and Anderson, 2003).

Three different stages are considered to be part of the decomposition process: Catabolism, in which the chemical changes are brought about by mineralization; Comminution which results in a physical reduction in the shape of the organic particles and a redistribution of the chemically unchanged litter. In comminution there are the following stages: 1st litter is broken down to small pieces which can be chemically reduced and 2nd, micro-organisms like bacteria and fungi reduce even more the litter pieces of organic matter and are mineralized into basic organic molecules such as ammonium, phosphate, CO_2 + H_2O which can be available to plants, micro-organisms or be leached out of the system (Swift et al., 1979), and finally leaching, which transports the nutrients and elements to superficial profiles as well as the removal of labile resources mainly by the action of the water. These factors can vary according to the type of soil and location.

2.4.2 Physical and chemical factors in decomposition processes

Some of the physical chemical or climatic factors that can affect decomposition processes are humidity, aeration, pH, temperature, O_2, CO_2 and or their combination, which are directly related to the growth of the decomposer colonies of bacteria and fungus, depending as well on the nature of the resource quality of the organic matter being decomposed.

As Heal et al., (1997) state, soil conditions and climate cause the main variation in the chemical composition of plant tissues through selection of plant species and their major life form (annual, deciduous or evergreen perennial etc). The distribution of ecosystem types determined by the character of their vegetation is broadly correlated with climatic conditions (Swift et al., 1979). Environmental factors such as light (Covelo and Gallardo, 2004; Rice and Bazzaz, 1989), carbon dioxide (Tuchman et al., 2003; Cotrufo et al., 1995), temperature (Dury et al., 1998), ozone (Findlay et al.,

1996) and soil nutrient status (Wait et al., 1998; Marschner, 1995; Bryant et al., 1993; Cornelissen, 1996), also affect the biochemical composition of plant structures.

The availability of nitrogen (N) alters the biochemical composition of plant tissues more than any other mineral nutrient (Bonilla and Roda, 1990; Marschner, 1995). The magnitude of a plant's response to external factors is pre-determined by growth strategy (Cornelissen, 1996) and genotype (Keinanen et al., 1999), and the extent to which traits of living plant parts are retained in litter depends upon the internal re-mobilisation of compounds during senescence (Aerts, 1995). As Swift et al. (1979) state, in humid climates where temperature and humidity are less constraining, the rate of decomposition depends mainly on the soil properties, humus and litterfall quality, unlike other latitudes where the litterfall decomposition depends on the climate (boreal regions and mediterranean regions). Climate, soil and the quantity and quality of organic material can affect directly the development of the organic decomposer colonies on the forest floor (Alvarez-Sanchez, 1995; Aerts, 1997).

2.4.3 Quality of leaf litter

The term litterfall quality refers mainly to the content of nutrients and comparative speed of decomposition of the residual plant organic matter (Anderson and Swift, 1983). The type of litterfall that is considered of high quality is one that has a high nutrient content, especially nitrogen and that is able to be decomposed quickly. Conversely, residual and other lignified materials, such as branches, some leaves, and the straw of cereals, are more resistant to decomposition and therefore of lower quality. Nevertheless, there exists an interspecific variation in the quality and amount of litterfall produced by different species, the reason why decomposition (and therefore, the cycles of C and N), are determined by the characteristics of the dominant species that compose the system (Anderson et al., 1983). These litterfall decomposition rates are regulated by a series of hierarchized bio-physical factors (Sariyildiz and Anderson, 2003), with fungi and bacteria as decomposition agents.

Nutrients such as N, P and C are those that influence in a greater way the first stage of decomposition and a post-leaching process in which is carried out mineralization and humification of lignin, cellulose and other compounds (Swift et al., 1979), and act as

the principal agents in the deceleration of the decomposition process (Jensen, 1979; Aber and Melillo, 1980; Aber et al., 1990; Preston and Trofymow, 2000). Soil leaching downward of soluble compounds whose C and N are progressive mineralized or immobilized (Heal et al., 1997). The leaching and post-leaching processes are carried out by means of a succession of decomposer micro-organisms such as fungi and bacteria, besides the physical chemical environmental factors (Jensen, 1979; Hammel, 1997). Soils besides climate are two fundamental factors for the quality of the leaf litter in the system (Heal et al., 1997).

The chemical composition of the litterfall can also influence in a direct way the rates of decomposition and the rate of reduction of the components of the litterfall, by means of the resistance of material to microbial attack which is a function of the amount of lignins waxes, and fats components of the litterfall (Havlin et al., 1990). The transfer of nutrients and secondary compounds between litterfall or by influence of the descompositor community, through the transport of secondary compounds or nutrients by means of fungi hiphae, although this movement of nutrients between litterfall can be carried out as well through the washing of nutrients (leaching).

2.4.3.1 Chemical quality parameters of leaf-litter

As Mafongoya et al. (1997) Vitousek states, different parameters have been used to measure the quality of litter such as C, N, lignin and polyphenols (Palm and Sanchez, 1990; Constanides and Fownes, 1994; Tian et al., 1997; Jama and Nair, 1996; Handayanto et al., 1997; Myers et al., 1997) all, are valid but have advantages and disadvantages each. Some ratios as C-N, Lig-N and other variations have been developed to explain the litter quality but usually the C:N is considered most significant.

However C:N ratio is widely accepted as a general index of quality, the relative importance of other parameters in different resources as a matter of discussion and research. Decomposition and nutrient release patterns of organic matter are determined for the organic constituents and the nutrient content of the organic matter, the decomposer colonies and the environmental conditions. A minimum data set can

be measured with quality parameters besides the data about climatic and environmental factors and soils information.

When these parameters are analysing in litter samples, is important to prepare samples of many plants growing in the same place, to assure that the field variability is included, according to Palm and Rowland (1997) these parameters are (Table 2.4):

Table 2.5 Important parameters to characterize plant input quality for decomposition and soil organic matter studies.

Parameter	Short term Decomp/Nutrient release	Long term Decomp/SOM formation
C quality		
Lignin	X	X
Soluble C	X	
Soluble phenolics	If %N >1.8 X	?
α cellulose		X
Nutrient Quality		
Total N	X	X
Total P		
Total C		
Ash-free dry weight	X	
Physical Quality		
Specific leaf area	X	

Source: Palm and Rowland (1997). Note: X indicates importance for the decomposition process.

2.5 Soil organic matter

Soil organic matter (SOM) conservation in the ecosystem is one of the most important components for the re-cycling of nutrients and sustainability of the tropical forests ecosystems of native forests, secondary vegetation and disturbed ecosystems. The SOM provides additional exchange sites for cations, thereby decreasing leaching potential. Organic N is bound in the SOM and it is released more in synchrony with the plant needs than it would be as nitrates or ammonia, which are the common forms of inorganic nitrogen in mineral soil (Brady and Weil, 2002), SOM can make the soil less susceptible to erosion as well as being the source of energy of micro-organisms whose activities renders the soil more permeable to roots (Jordan III, 1988;

Montagnini & Jordan, 2005). So the SOM is important in the cation recycling, nutrient availability and maintenance, sequester of N and erosion prevention (Kochy and Wilson, 1997).

2.5.1 Organic matter decomposition rates

Jenny et al. (1949) and later Olson (1963), proposed a formula to calculate the loss constant or decomposition coefficient. These formulas have been used to calculate the rates of decomposition of organic matter in different climatic regions and with different types of matter in decomposition (Swift et al., 1979). This method can be used as well in the determination of the litter loss rates in the forest floor and to calculate the rates of mineralization of the organic material and even for the turnover times of various fractions of the litter material (Reiners and Reiners, 1970). The "k" value represents the rate of organic matter decomposition, and 3/k is the time required for 95% of the organic matter to decompose. Decomposition rates that have been studied in different biomes, show that the organic matter is decompose at higher rates in tropical forests, but Anderson and Swift (1983), showed that the decomposition rates of the litter in tropical forests can have wide variations within a single region and so, concluded that the variation within single regions is too great to permit statements about the differences on decomposability between tropical and temperate regions.

Table 2.6 Decomposition constants k and 3/k in six different ecosystem types

	Tundra	Boreal forest	Temperate deciduous forest	Temperate grassland	Savannah	Tropical moist forest
K year	0.03	0.21	0.77	1.5	3.2	6.0
3/k year	100	14	4	2	1	0.5

(Adapted from Swift *et al.* 1979)

The rate of decomposition can be affected among other factors by the differences in quality between the leaf-litter of different tree species and many different properties of the litter itself (Staaf, 1980; Fisk et al., 1998; Chadwick et al., 2001; Gartner and Cardon, 2004; Meier and Bowman, 2008). These factors can have a combined effect

in the speed of decomposition due to the mixture of species and its chemical components, altering the decomposition process to a faster decomposition (if it exists a greater amount of N and optimal conditions for the reproduction of white fungi in just a short time) or a slower one (greater concentration of lignin and cellulose), and also can affect the development of decomposer communities in the influence area of the litter compounds (Aber and Melillo, 1980; Aber et al., 1993; Chadwick et al., 2001). Preston and Trofymow (2000), however states that litter decomposition follows the same patterns as primary production and even when this pattern can vary widely in the tropics, rates are still are higher in the tropics than at high latitudes were the forests receive similar amounts of rain and the soils are very similar (Swift et al., 1979).

2.6 Summary

The trees are the main component of the tropical forests and the canopy serves as support for other life forms as animal, vegetal and inclusively fungi and bacteria. These as well, provide services and products to the environment and to the human populations that live on them. Between the products that are obtained from the forests are food products, fruits, medicines, wood, fuel, and including the aesthetic and recreational values of the zone. The services that grant many of these shade trees for the crops can be as erosion protection, carbon sequestration and nutrients uptake and mineralization and so that they can be available for the vegetal elements of the system, which is more important in the case of combination of trees with crops as it happens in the agroforestry systems, besides to conserve the biodiversity in deforested and fragmented areas in tropical zones.

Agroforestry is a good alternative to develop sustainable production systems but it must have characteristics approachable to farmers as a wide range of profitable and less resource demanding soil and water technologies (McDonald and Brown, 2000; Acharya, 2005), rustic and traditional coffee systems can be a good example of this.

Litterfall once deposited in the forest or plantation floor, becomes a part of the nutrient cycling through the process of decomposition of the organic matter and nutrient mineralization on the soil, and by the action of colonies of fungi, bacteria and

microbes, produces the mineralization of nutrients and with it their availability for the plants. These nutrients can play an important role for the development of crops and trees, such as it is the case of rustic and traditional coffee (*Coffea* spp) and Cacao (*Theobroma cacao*).

Litter production, its decomposition and the nutrient cycling are some of the most studied ecosystem processes, because of the importance as providers of nutrients into the ecosystem. The presence of native tree species, single or in group can be one of the determinant factors for the litterfall quality, which affects in a direct way to the rates of decomposition and the consequent nutrient mineralization in the soil.

This investigation looks to approach to the knowledge and study of the litterfall quality of dominant native tree species in the traditional (TCS), rustic (RCS) coffee systems and the remnant Sub-perennial medium forest (Spmf) and how it can affect the decomposition rates, this alteration could affect in a direct way to the nutrient cycling processes and availability of nutrients on the soil, as well could have other effects over the soil such as erosion and leaching of nutrients just to name some of the effects of the changes in the canopy species on these systems.

Chapter 3 AFS description in Traditional (TCS) and Rustic (RCS) coffee systems and Subperennial medium forest (Spmf) in San Miguel, Veracruz. México.

3.1 Introduction

Crops such as cacao and coffee form the base for many agroforestry systems of a simultaneous type (Licona et al., 1995; Beer and Somarriba, 1999). In most of the tropical regions where coffee is cultivated as a traditional system (as happens in Africa and Latin-America) it is considered as a multistrata polycultural system, where a diversity of tree species with multiple purposes, provides the function of shade for the crops (Raintree, 1989; Krishnamurthy and Avila, 2001). Agroforestry systems, specifically shaded coffee and cacao, because of their complex vegetation structure and richness can be an important biodiversity conservation tool in regions that are highly biodiverse as México, Ecuador, Peru, Tanzania and others (Somarriba, 2004). Nevertheless, the way to practice the coffee and the cacao production was basically diversified due to two causes, the socio-economic level of the farmer and the use given to the tree species canopy of the forest in these zones.

In México, Nolasco (1985), Moguel and Toledo (1999), Escamilla (1994) and Escamilla & Díaz (2002), described in general five coffee production systems with its respective canopy types and uses, these are: rustic coffee plantation or mountain system, in which canopy of the tropical forest is used and altered, but that conserves a greater percentage of the native species, Traditional polyculture or coffee garden, Commercial polyculture, Shaded monoculture and Unshaded monoculture which does not use the tree canopy at all.

Rustic coffee system is widely practiced by the coffee producers of the mountain range of Atoyac, due to its characteristics of self-consumption and low economic and technological production level. Some of the Atoyac mountain range belongs to some ethnic groups of Nahuatl origin although the majority is the racially mixed denominated as "Mestizos", but all commonly practice the rustic type of coffee production. Some of the main characteristics of the RCS are the low or null use of chemical inputs and minor agricultural labours, and are limited to a canopy and coffee

pruning and elimination of some shrubs that grow under the lowest level of the forest canopy, but most of the native species are conserved as part of the system as are the palms and some native tree species that may have some commercial or traditional uses. The traditional coffee plantations usually consist in a minor number of tree canopy species that have the function of providing shade to the coffee and can be sold as fuel or woody materials, in some cases, some trees as citrus and fruits can be used with the objective to have an additional income in the agroforestry system.

3.2 Materials and methods

3.2.1 Study area: Sierra de Atoyac

The Mountain range of Atoyac comprises of the Sierra Madre Oriental (Eastern mountain range) and it is in the region of great mountains in the central part of the state of Veracruz., which includes the municipalities of Atoyac, Amatlán de los reyes and Tepatlaxco, it is located 42 km from the city of Cordoba, Veracruz, with an altitude ranging from 750 to 1,400 meters above the sea level (m.a.s.l.), with a annual precipitation average of 2,500 millimeters and period of minimal rain from November to May, and annual average temperature of 22.5° C., a humid warm climate type (A) C' (m) w'o (García, 1987), with rain period over the summer and with soils classified as redzinas because of reddish coffee color and vertisols with neutral pH.

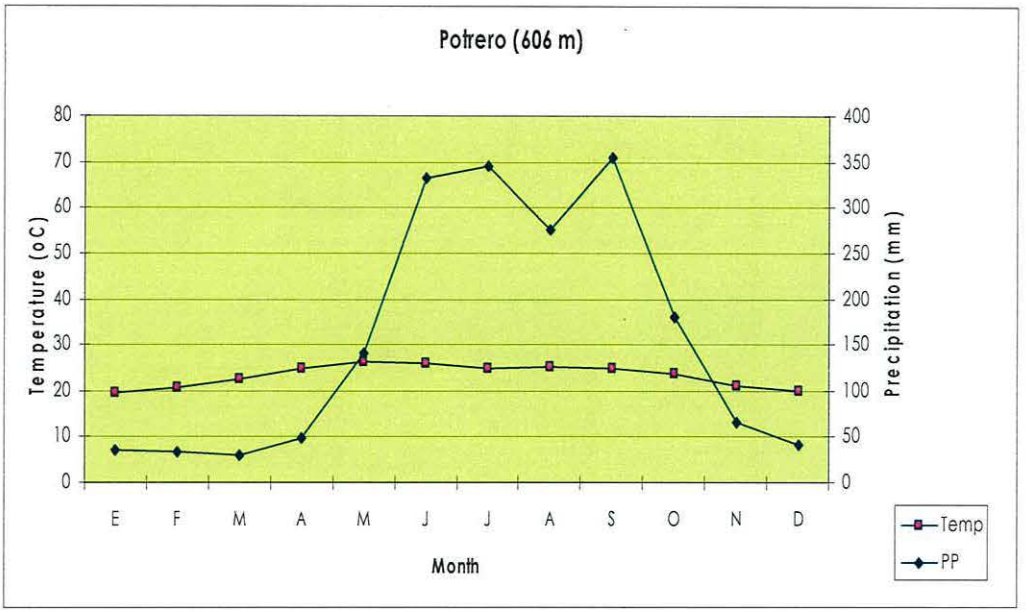
Table3.1 Climatic data: Potrero, Veracruz, México.

Altitude (a.s.l.): 660 m. Coordenades: 18°52", 96°50"

Years	J	F	M	A	M	J	J	A	S	O	N	D	Annual
T 36	19.6	20.7	22.4	24.9	26.2	25.9	24.8	25.2	24.7	23.5	21.1	19.9	23.2
P 36	34.9	33	29.4	49.1	140.6	331.6	345.5	276.9	355	179.5	65.6	40.7	1881.7

Note: T= temperature (Celsius); P= precipitation (mm).

Source : García, (1987).



Source: Villavicencio (2002).

Fig. 3.1 Cimatic diagram Potrero, Veracruz. México.

Note: Areas in aquamarine are perennial and subperennial medium forest. ☆=San Miguel, Veracruz.

Map source: Google Earth, México. (2009).

Fig. 3.2 Localization of the study zone in México.

3.2.2 Relief and soil types

The relief consists of a series of small mountains and hills, with concave-convex topography and narrow folding and di-sectionated hills. Hillocks and wavy slopes of more than 15 % exist of convex form, whose altitude varies from 350 m, where is developed mainly the riparian vegetation (Rzedowski, 1978), to 950 m a.s.l.

Geology

The geologic plinth that is located in the Mountain range of Atoyac has a NW-SW orientation, constituted by limestone sedimentary rocks of tertiary superior of karstic nature. In this type of rocks the drainage and the draining are fast, due to the strong slope of the land and to the porosity of the material. This has influence in the development of the coffee plants and trees of shade since due to the fast water infiltration, the plants do not have sufficient time to absorb it and to use it in their development (Gómez-Pompa, 1978).

Soils

In México 25 soil units exists from 29 classified by FAO/UNESCO (2007). Some of the most representative soils in Mexico according to the FAO/UNESCO classification (1975) adopted by INEGI (1991) are: Leptosols, Regasols, Calcisols, Feozems and Vertisols which together cover 69% of the country area. Leptosols are the most representative with 24%, followed by Regasols and Calcisols (19 and 8% respectively), these soils are characterized for being superficial with low humidity, high Ca and being highly erodible and not suitable for the agriculture (INE, 2004: SEMARNAT, 2005). The most fertile soils and therefore most exploited are Feozems (10%), Vertisols (8%), Cambisols (5%) and Luvisols (3%) which together cover 26% of the total area (SEMARNAT, 2005). These soils are in most cases over-exploited by the intensive agriculture that threatens its productive capacity. The greater soil diversity is located in the regions Centre and Gulf of México, where the population that lives in these regions exerts pressures on the resource.

In Veracruz State, México, Vertisols are the most representative soil type with a cover of 46.82% (%) followed by Alisols (24.46%), Feozems (7.7 %), Cambisols (7.42%),

Luvisols (6.5 %), Andosols (4.35 %), and others (INEGI, 2005). The predominant soils in the Atoyac range are mainly Vertisols and Rendzinas of dark brown colour, with presence of abundant organic matter (Pennington and Sarukhán, 1998).

Vertisols are characterized because of their black colour and a high concentration of clays that produce a presence of crevices during the driest season of the year. Even when this type of soil appear in almost all the climates that have a very well established rainy and dry season, pedologically differs from other soils in the tropics because is dominated by montmorillonitic clays and presents a low susceptibility to erosion (Young, 1976; Landon, 1991; Castellanos et al., 2000). It can be found on flat lands or in depressions, and it is frequent in the coastal plains of the Gulf of México usually associated with Feozem and the Solonchaks. It is part of a group of soils that comprises clayey soils of expansible and extremely plastic nature. With the adequate management this soils are considered as moderately good for agriculture but difficult in their mechanization.

According to the soil taxonomy these soils are included in the Vertisol order, Ustert or Torrent suborder and the Pellustert Great Group (Bornemisza and Alvarado, 1975). Other characteristics are Clay >30% 0 to 50 cm, cracks >1 to 50 cm wide and in general are considered to have low concentrations of P and K but high in Ca (in form of $CaCO_3$). The types of Vertisols according to FAO/UNESCO classification (2007) are: Calcic, Eutric, Dystric and Gypsic with $CaCO_3$ accumulation in case of the Calcic Vertisols (Landon, 1991).

3.2.3 Ecology

In México there are a total of 35 vegetation types (Rzedowski, 1978) in two distinctive zones, the Neartic, which occupies the mayor part of North America and includes the Arid and Semi-arid zones of the United States and the central and northern parts of México, the templates and cold zones of the Sierra Madre Oriental and Occidental and the volcanic ranges as well. Some of the faunal species are: Black bear (*Ursus americanus*), American badger (*Taxidea taxus*), Lynx (*Lynx* sp.), Wolf (*Canis lupus*), Black tail deer (*Odocoileus hemionus*), Cimarron ram (*Ovis canadensis*), Sonorean proghorn (*Antilocapra americana*), Kangoroo rats (*Dipodomys*

spp.), Prairie dog (*Geomys* spp.), Road runner (*Geococcys* spp.), Chamaleon or Tepayatzin (*Phrynosoma* spp).

The Neotropical zone includes zones as the warm humid and sub-humid low-land and some high-lands in the Chiapas mountain range and Sierra Madre del sur (Mother mountain range) as well all the Caribbean and Central and South-america. Some of the typical species in these zones are: Jaguar (*Felis onca*), Ocelote (*Felis pardalis*), Coatí (*Nasua nasua*), Bairds tapir (*Tapirus bairdii*), Spider monkey (*Ateles geoffroyi*), Sarahuato (*Aloutta* spp.), Vampire (*Desmodus rotundus*), Tepezcuintle (*Cuniculus paca*), Armadillo (*Dasypus novenicintus*), Tlacuache or Zarigüeya (*Didelphis virginianus*), Chachalaca (*Hortalis vetula*), Tucán (*Rhamphastos suifuratlis*), Iguana (*Iguana iguana*), Garrobo (*Ctenosaura* spp.), Boa (*Constrictor constrictor*). Some of the main ecosystems are: high and medium tropical forests, low forests and associated bushes, rain forests, temperate forests, tropical coastal ecosystems.

Based on the classification of Miranda and Hernández-Xolocotzi (Gómez -Pompa, 1978), the following types of vegetation were identified: a) Subperennial medium forest, which is the vegetation unit that characterizes to the mountain range of Atoyac; b) Riparian vegetation, distributed throughout the hidrologic network which grows on the sides of the Atoyac river and which Rzedowski (1978) also called with the name of Gallery forest; and c) Secondary vegetation that is derived from the clearing of the subperennial medium forest and have a considerable extension cover within the zone of study.

The subperennial medium forest (Spmf) is characterized because some of the trees (25 to 50%) shed their leaves during the drought season, It is present in extensive areas with average temperature annual of more than 20°C and greater the average precipitation 2,500 mm per year (Gómez –Pompa, 1966, Gómez -Pompa and Nevling, 1970, Chiang, 1970), there is a dry season from the end of November to May/June with some rains during the months of March. It is dense and rich in lianas and ephifytes and presents several layers (multistratified). The height of its tree component is 25m in average and exceptionally some elements can reach 35 m height, usually located in the base of hills (Chiang, 1970).

Some of the dominant tree species that constitute this type of tropical forest are the same of those in the Subperennial high forest dominant species as: *Brosimum alicastrum, Bernoullia flammea, Bursera simaruba, Robinsonella mirandae* and *Cordia alliodora*, among others (Chiang, 1970). Some of the representative species in the secondary vegetation are *Astronium graveolens, Brosimum alicastrum, Spondias mombin, Dendropanax arboreus, Cecropia obtusifolia, Protium copal, Inga* sp. and *Bunchonsia lanceolata*, among others.

Table 3.2 Tropical forest types of vegetation in México (Approx. equivalencies)

Rzedowzki (1978) (México)	**Leopold (1950)**	**Miranda and Hernández-Xolocotzi, (1963) (México)**	**Flores et al. (1971) (México)**	**INEGI (1997) (México)**
Evergreen tropical forest (Bosque tropical perennifolio)	Rainforest, tropical evergreen forest	Evergreen high forest, Semi-evergreen high or medium forest. (Selva alta perennifolia, Selva alta or mediana subperennifolia)	Evergreen high forest, Semi-evergreen medium forest. (Selva alta perennifolia, Selva mediana subperennifolia)	Evergreen high forest, Semi-evergreen medium forest, High subperennial semi-evergreen forest. (Selva alta perennifolia, selva mediana subperennifolia and selva alta subperennifolia)
Sub-deciduos tropical forest (Bosque tropical subcaducifolio)	Tropical deciduous forest (part).	Semi-deciduous high or medium forest. (Selva alta o mediana subcaducifolia)	Semi-deciduous medium forest, Semi-evergreen medium forest (part). (Selva mediana subcaducifolia, selva mediana subperennifolia(part))	Semi-deciduos medium forest (Selva mediana subcaducifolia)
Deciduous tropical forest (Bosque tropical caducifolio)	Tropical deciduous forest (part), Arid tropical scrub	Deciduous low forest (Selva baja caducifolia)	Deciduous low forest (part) (Selva baja caducifolia (part))	Deciduous low forest (Selva baja caducifolia)

Note: In parentheses, type of vegetation in spanish

3.2.4 Study zone localization

The municipality of Amatlán de los Reyes is located to 18°51′ latitude North and 96°55′ longitude West , at a height 830 m.a.s.l. and with a total surface area of 148.88 ha. The northern limit is the municipality of Córdoba and Atoyac, to the south with Coetzala and Cuichapa, to the east with Yanga and the west with Córdoba.

The municipality has a total population of 38,425 people and 74 localities, of which 70 are rural locations. San Miguel is located at km 17 on the Córdoba-Mirador highway at an altitude of 727 m.a.s.l., it have a total surface of 148.80 ha and represents 0.2 % of the state total area (Gobierno del Estado de Veracruz, 2001). The economy is based on the agricultural production, with products such as sugar cane, coffee and timber.

3.2.4.1 Study site characteristics and plots.

Based on the descriptions of the canopy structure and species use and type (native or exotic) by Moguel and Toledo (1999) and characteristics such as canopy height the following systems TCS, RCS and Spmf were described. In a random block design, nine plots of 1000 m^2 (20×50 m) were randomly selected and localized with GPS (Annex 1), three for each system: TCS, RCS and Spmf (Fig 3.3),. A Humid warm climate ((A) C (m) w" o) (García, 1987), and an average annual rainfall from 1,850 to 2,500 mm, an annual average temperature of 22.5° C, with a drought period (from November to end of May) and a rain season (from end of May to December) well defined. The predominant soil type is Vertisols of dark brown color, with presence of abundant organic matter (Chiang, 1970; Pennington and Sarukhan, 1998), and the relief is developed on a series of hills, with concave-convex topography and narrow foldings with disectect hills with slopes of more than 15%, whose altitude varies from 724 to 819 m.a.s.l.

Fig. 3.3 Localization of the study plots in San Miguel, Veracruz. México.

Note: ★=Spmf, ★= TCS, ★ =RCS, San Miguel=☆, Manzanillo=☆. Map source: Google maps (2009).

3.3 Results

3.3.1. Biophysical characteristics

Vegetation

In agreement with Miranda and Hernández-Xolocotzi vegetation classification (1963) and Gómez-Pompa (1978), the following types of vegetation were identified: a) Forest subevergreen median, vegetation unit that characterizes the Mountain range of Atoyac; b) Riparian vegetation, distributed throughout the hydrologic network that forms the Atoyac River and to which Rzedowski (1978), mentions it with the name of Forest of Gallery; and, c) Secondary vegetation that derives from the clearing of the Subperennial medium forest and that has a considerable cover area within the study zone.

Subperennial medium forests (Spmf)

It is characterized because some of the trees (25 to 50%) lose their leaves in the most accentuated of the drought season. Some of the dominant tree species are the same of the Subperennial high forest; it is one of the types of vegetation present in big areas in the warm-humid tropical zones of México. It is distributed from the South border with Guatemala to almost reaching the limit line of the Tropic of Cancer. It is widely represented in the slope of the Gulf of México, although its area of distribution also includes to the Pacific and extensive areas of the Yucatan Peninsula, adding a total of 84.227,70 km^2. It is distributed with a small portion in the state of San Luis Potosí (Tamasopo, Aguas Calientes, El Naranjo) and up to the south of Tampico in the state of Tamaulipas in its more boreal portion. Also some small portions of this vegetation in the states of Nayarit and Colima exist.

The structure and appearance of the vegetation is dense and rich in lianas and ephyfites with several layers in the canopy (multistratified), which can show some difficulty to be appraised clearly. The average height of the tree component is about 25 to 30 m., exceptionally some elements reach the height of 35 m, being located in the base of hills as are *Ficus* sp.

Spmf - Representative species

Some of the dominant species which form part of the Spmf excel: *Brosimum alicastrum, Bernoullia flammea, Bursera simaruba, Robinsonella mirandae* and *Astronium graveolens* among others. Some of the representative dominant species on the secondary vegetation are: *Brosimum alicastrum, Cordia alliodora, Spondias mombin, Dendropanax arboreus, Cecropia obtusifolia, Protium copal, Inga sp.*, and *Bunchonsia lanceolata* among others. (Pennington and Sarukhan, 1998; Chiang, 1970; Gómez-Pompa, 1978).

3.3.2. Agroforestry characterization

In order to carry out this description from the agroforestry point of view, it has been reviewed some study cases done in the study zone in Tlapacoyan, by Krishnamurthy (1998), Sierra de Atoyac, Veracruz (Villavicencio, 2002), beside the study cases of Lagermann and Heuveldop (1983), Nair (1989) and Montagnini (1992).

This analysis is based on the general theory of systems which suggests that for understanding the operation of a system is required to know each one of the elements that form part of it (Lagermann and Heuveldop, 1983). The coffee and cacao crops are the base for many simultaneous agroforestry systems (Beer, 1999; Beer and Somarriba, 1999).

For the description of the selected area and a consequent analysis of the Rustic and traditional coffee system, the methodology focuses on the criteria established by ICRAF (Torquebiau, 1990), to analyze structural and economically the agroforestry system and to discuss the information generated by means of this investigation.

Structural analysis of the AFS

This analysis consists in defining the presence of the components of the system, locating its nature and to describe its adjustment in time and the space (Huxley 1983; Nair, 1989, 1997). For Torquebiau (1990), the physical location of the components (mixed, zonal, dense, dispersed and with simple layers or multilayers), and the

temporary adjustment (simultaneous, sequential, relay, superimposed-intermittent, interpolated, concomitant) are the main characteristics to describe in a system.

Functional analysis of the AFS

In this analysis is important to identify the incomes and outcomes of the system, these can be in form of biochemical inputs and products and the processes that are generated among them. In general it is possible to distinguished between two types of incomes and products, those that are of the bio-physical type as the water, solar energy, soil nutrients, shade, control of the erosion, etc., and those which are of socio-economic type, as products that can be bought, sold or be quantified in economical terms as are the terrain, agricultural equipment, seeds, plants, work, etc. Once the consumptions and products are known, it is possible to analyze the AFS from the economical management point of view (administration and productivity). About the performance of AFS, it can be quantified as the relation between the inputs and outputs or products of the system, which can also be seen as an efficiency measurement (Relation Benefit/Cost). The biological or ecological efficiency of a system depends to a large extent on its technical performance, for example, by means of the total production of biomass/ha.

3.3.3. Socio-economical Aspects

Soil use and land tenancy

The community of San Miguel municipality of Amatlán de los Reyes, has a total area of 74 ha, all are small private properties. Almost the totality of this area is cultivated with coffee, in which the used varieties on traditional and rustic coffee systems are Typica and Robusta (*Coffea arabica* and *Coffea canephora*). Other products operated in this community are the palms *Chamaedorae elegans, Chamaedorae tepejilote* and *Chamaedorae sartorii*, only *Chamaedorae elegans* reaches a good price in the market.

The commercialization of the forest species has been practiced intensively, and a consequence of it, a large number of woody species has been depleted and diminished

in a considerable amount, some of theses species as *Cedrela odorata* and *Juglans* sp., has almost disappeared in some parts of the Atoyac range. The extraction of timber is pointed mainly in the species as *Cordia alliodora* and *Dipholis minutiflora* which have an economical average value in the market.

Agricultural activity

The main crop practiced in this community is the coffee in traditional and rustic systems, which in the case of the RCS are associate to a high diversity of tree species that comprised of the original vegetation of Spmf. *Coffea arabica* and *Coffea canephora* (Typica and Robusta varieties) are the representative species for both systems (Table 3.3), which are well adapted the terrain conditions and although low productivity, are able to produce a coffee with good body and flavour.

Table 3.3 Coffee plants inventory in San Miguel, Veracruz. México

Coffee varieties (Number of plants)					
Robusta	**Bourbon**	**Garnica**	**Typica**	**Caturra**	**Total**
---	31,635	28,120	8,436	2,109	70,300

Note: no data available for the Robusta (*Coffea canephora*).

Source: Bucio-Alanís and COLPOS (2001).

Other two agricultural products that associate to RCS are commercial palms as *Chamaedorae elegans, Chamaedorae tepejilote* and *Chamaedorae sartorii* and the timber from species as *Cedrela odorata, Cordia, alliodora* and *Dipholis minutiflora* and other tree canopy species, which are sold mainly for the local market of furniture and transport bodies for sugar cane.

3.3.4 AFS description of the rustic coffee system (RCS)

The vertical adjustment in RCS is multistratified, with a great number of representative Spmf canopy tree species and secondary vegetation type of this region. The age of the coffee plantations is in average 70 years old (Bucio-Alanis & Colpos, 2001) and the height of some of the canopy tree component that can reach up to 30 m. (Chiang, 1970) which contributes to create highly heterogeneous stratification (Table

3.4), this canopy characteristic can be considered as the closest to native vegetation in an agricultural system of the zone, although it is possible to recognize another two layers that are formed clearly, one is the made up of the coffee plantations that already have been described previously and that can reach a height to of 7 m, and a lower strata compose of native plant species such as palms and *Yucca elephantii*, which can reach up to 1.8 to 2 m height.

The existence of open spaces on the floor level is due to the presence of existing limestone in slopes of hills of the zone of study or to trees that have been used or commercialized, on these spaces usually grows plants, bushes or representative trees of the secondary vegetation of the zone. Some of the most important species because of their economical value are the citrus and woody species as: *Robinsonella mirandae, Cedrela odorata, Dipholis minutiflora* and *Cordia alliodora*.

The management of the RCS usually lacks any type of chemical inputs and/or any mechanized labor in the coffee plantations that includes professional advisory. The agricultural labours are limited to the clearing the forests floor of some bushes and plants that the farmer consider of negative impact or no use for his system, usually are done before and after the harvest and that includes a minimum and occasional pruning on the canopy trees and coffee plants. Other agricultural labours include the cut and production of the commercial palms and minor timber species which are associated with the coffee plants. From these varieties, Bourbón and Typica are of early maturation, Caturra variety and Garnica are late maturation. The average yield per coffee plant is 1.80 kg, with a total produced in the community of 125,540 kg. Some of the uses of the tree canopy are timber, construction, fuel, food, medicinal, shade and even aesthetical and ornamental values.

The tree canopy species with some uses are: *Cedrela odorata, Cordia alliodora, Dipholis minutiflora, Pithecellobium arboretum, Robinsonella mirandae* as timber; *Mangifera indica, Citrus sinensis, Malinkara sapota,* and *Anona* sp. as fruit trees, *Croton draco, Exostema mexicanum* and *Cordia diversifolia* as medicinal among others.

Other species that also form part of the system and which lack apparent use or economic value such as "Izcoahuite", *Vatairea lundelii, Vernonia patens, Stemmadenia donnell-smithii* have an important role in the ecological health of the AFS and for the conservation of the diversity of species of insects which help to maintain a balance in the presence of plagues and potentially dangerous diseases (Guharay et al., 2001).

Economically valuable tree species such as *Cedrela odorata, Cordia alliodora,* and *Dipholis minutiflora*, are used mainly for furniture and construction industry. About the presence of these species in the sampled parcels, *Cedrela odorata* is the species that has minor frequency due its extraction in the entire zone because of its value on the wood market. *Cordia alliodora* and *Dipholis minutiflora*, are being conserved, but because of the commercial value that they have but a number of other native species were found in small numbers on the sampled plots and it will represent a future disappearance if this trend continues.

3.3.5 AFS description of the traditional coffee system (TCS)

The coffee systems in México began with the management of the shade that is provided by the native vegetation in the tropical zones. With time, development and specialization of the crop, consequently also improved the shade provided by specific trees, modifying in this way the shade species canopy composition and structure in the coffee plantations. Mainly the traditional systems (TCS) are carried out with two varieties of coffee, Typica and Robusta (*Coffea arabica* and *Coffea canephora* respectively) and with some native and exotic species.

TCS is an agrisilvicultural system of simultaneous type; retaining the characteristic of being perennial and growing together at the same time. The vertical arrangement is dispersed and mixed, since all the plants have been placed in an irregular way (Torquebiau, 1990), without having an order defined as far as either spaces or number of plants by hectares and it is based on the experience. The horizontal arrangement is dense, because the high number of individuals by parcel which is around 1,350 coffee plants, 3,500 palms and 1,000 trees average per ha. Some of the main tree species are *Mastichodendron capirii* (the most used tree as shade) and some other trees as *Citrus*

spp, *Mangifera indica, Inga* sp and *Cecropia obtusifolia* besides *Dipholis minutiflora, Cordia alliodora*, and *Cedrela odorata*.

The uses of the tree canopy species are mainly two: Timber and non-timber (usually coffee or other fruits). The palms (*Chamaedorae. elegans, Chamaedorae tepejilote* and *Chamaedorae sartorii)* as well as the RCS, can represent an additional economical income in the system, these palms usually grown wild between the native vegetation of the Spmf, but are planted by the farmers in the TCS. The management of the palm consist only in finding an optimal place for its reproduction, with sufficient shade and humidity to avoid the stress per higher temperatures, mainly during the drought season. The leaves cutting is carried out continuously from the third year of life of the plants at the rate of a leaf per month, during the rain season which lasts 7 to 9 months a year.

3.3.6. Functional analysis of the system

It is generally possible to distinguish two types of inputs, those of bio-physical type and those of economic type (Torquebiau, 1990; Nair, 1997). The bio-physical ones are those that do not produce any economic cost, as the solar light, precipitation, soil or atmospheric nitrogen, control of the erosion, among others. Meanwhile the economical inputs are those that generate some economic cost, as fertilizers, agro-chemicals and agricultural laboring.

3.3.6.1 Average and resources limitation

As part of the context to the approach of systems, the word "function" means more as a form to describe or to analyze the objectives and management, for which it is necessary to identify the consumptions and the products that comprise the development of the system. Although the type of soil it is considered good and fertile for this zone, the greater limitation is based in its geologic origin of karstic nature that is susceptible to erosion. This same nature of the land nevertheless causes good soil aeration and a good drainage and is the reason why floods in the zone do not exist.

The mechanization of the coffee plantations is difficult due to the terrain slope (approx. 20°), reason why the agricultural labour are done manually. Although frosts in the zone do not exist, the period of drought can last up to four months, which would cause damage to the coffee plants, mainly if this lasts until the stages of flowering and harvest. The high temperatures during the months of April and May can also cause damage during flowering.

3.3.6.2 Economical income

The economic income average by family is $50.00 Mexican pesos per day (about £2.4), and an average number of 5 persons per family. The family economical income depends on the coffee production and field labour mainly (Bucio-Alanís & COLPOS, 2001). The lack of basic services like potable water and sewage system, the failure of the governmental programs and the crisis of the coffee market have caused a strong diminution in the standard of life of the population in the coffee production zones. This situation has a negative impact in the management of the coffee plantations in the community, because when the producer does not find a market that can economically be feasible for him, prefers to abandon the crops and agricultural labouring and to emigrate towards zones where can obtain better economical inputs by means of remunerated work as city workers. The most common cities to emigrate are Córdoba and Veracruz port (Veracruz), México City and the United States of America.

Other negative effect that the socio-economical conditions have in the coffee plantations is the constant use of the forest resources as the economical valuable timber as *Cordia alliodora* and *Dipholis minutiflora* which before were considered as a minor valuable timber than *Cedrela odorata, Juglans* sp., *Tabebuia roseae*, and *Sickingia salvadorensis*, which exist only in low densities per ha. The coffee produced is described as "organic" that is to say, that has not been used any type of agro-chemical during its process. The environmental and physical-chemical conditions in the Mountain range of Atoyac are optimal to produce organic coffee in traditional and rustic systems, but unfortunately, the lack of proper channels to commercialize and process the coffee don't increase the total value obtained by the farmers in the market.

3.3.6.3 Establishment and management

The first coffee plantations in the region were establish around 150 years ago, but for the community of San Miguel it was probably around 8 decades ago and for the last three decades there has been an improvement in production, due to the state programs such as the implemented per INMECAFE in Veracruz. As far as the system management, the only agricultural labours that are performed are two "chapeos" or clearing of branches and weeds, one before and another one after the rain season to eliminate shrubs and weeds that difficult the operations of harvest and the production of the coffee plants. Besides this, there are not any type of labour practiced, as are pruning, fertilizations or controls of plagues and diseases in which it is applied agro-chemicals, nor works of soil conservation (Table 3.4).

The reason why these labours are not carried are mainly because of the topographic conditions of the terrain and because the cost of the agrochemical products, which does not allow the farmer to improve the management and quality of the crop. The market coffee prices is another limitation in the commercialization of the coffee. Instead the more technified management of the crop is applied the farmer empirical knowledge about the coffee cultivation and the natural control of plagues and diseases where a balance by means of the diversity involving insects, micro-organisms, animal and vegetal species in the system (Guharay et al., 2001).

Table 3.4 Calendar of agricultural activities in the TCS and RCS

Crop / Activity	J	F	M	A	M	J	J	A	S	O	N	D
Coffee												
"Chapeo"			X									X
Harvest						X	X	X	X	X	X	
Palms												
Sowing						X	X	X	X			
Weed										X		
control				X		X			X	X	X	
Harvest			X	X	X							
Woody trees	X	X	X								X	X
Felling												

3.3.6.4 Function and service of the system

Some of the principal services that are performed by the tree component are the shade protection to the coffee crop as well as protection against winds and rain for the culture of the coffee, the environmental nitrogen fixation, humidity and soil conservation. About the economical benefits, previously it was possible to consider the coffee as the most important input but this situation changed because of the prolongation of the crisis in the coffee market, where a reduction in the economical value has provoked the producers to stop harvesting in order not to have economic losses. The timber trees contributes with the biggest economical income, with a sell of 7 trees per ha/yr average, have a direct increment in the economy of the farmers (Table 3.5).

Table 3.5 Timber trees economical characteristics in TCS and RCS.

A. Investment budget	**Cost**	
Land	Private	
Trees	Private	
B. Outcome		
Motosierra (incl. Felling and cut)	$1.00 / foot^3 ($350.00 average / tree - £17.50)	
C. Incomes (Value of the production)	**Price in dry weight**	**Average value per tree**
Cedrela odorata	$ 8.00 foot^3	$ 2,800.00 (£140.00)
Cordia alliodora	$ 6.00 foot^3	$ 2,100.00 (£105.00)
Juglans sp.	$ 5.00 foot^3	$ 1,750.00 (£87.50)
Dipholis minutiflora, Robinsonella mirandae	$ 4.00 foot^3	$ 1,400.00 (£70.00)
D. Net profit	**Ratio B / C (Average)**	
Average felling 7 trees / year	$ 14,350.00 and $ 16,750.00 / year	
	£ 717.50 and £ 837.50 / year	

Palms contributes a small but constant input to the farmer's income. Palm leaves are usually collected during 8 months of the year (Table 3.6).

Table 3.6 Economical characteristics of palm production.

A. Investment budget	**Cost**	
Land, "Chapeos" (2 per year) and Plants	Private	
B. Outcomes		
Leaf cutting, others.	1 leaf per month, 8 per plant / year	
C. Incomes (Value of the production)	Production per ha.	Total / year
Chamaedorae elegans	$ 12.00 gruesa	24 gruesas / año £116.65
Chamaedorae tepejilote	$ 7.00 gruesa	12 gruesas / año £ 4.20
Chamaedorae sartorii	$ 5.00 gruesa	7 gruesas / año £ 1.75
D. Net profit	**Ratio B / C**	
Chamaedorea elegans, Ch. tepejilote and Ch. sartorii	$ 2,452.00 / ha / year- £122.60	

Note: One "gruesa" are 144 palm leaves.

The economical inputs of the two systems (TCS and RCS) was the same but the output (as coffee) was higher in the TCS (Table 3.7), because of the canopy shade management and lower in the RCS (Table 3.8) where the use of a higher diversity of trees may affect the coffee total production but contributes more to the family income in form of self-consumption crops or fruits.

Table 3.7 Economical characteristics of the coffee production in TCS.

A. Investment budget	Cost
Land tenancy Coffee plants	Private Private
B. Outcomes Chapeos/clearance (2 per year) Transport, Stock, Consultancy, Industrial processes, Others. Total	 $ 160.00 / year (£8.20/year) $ 0.266 / kg. Coffee **cereza** $ 465.00 / ha / year (£23.25) $625.00 /ha / year (£32.02)
C. Incomes Value of the production (Typica and Robusta) Total	 $ 1.17 kg **cereza** (£0.0585) 2,750 kg / ha $ 3,217.50 /ha (£165.00)
D. Net profit Species Typica and Robusta Total	Ratio Benefit/Cost $0.904 kg **cereza** (£0.04635) $ 2,486.50 / ha / year (£127.48)

Table 3.8 Economical characteristics of the coffee production in RCS.

A. Investment budget	**Cost**
Land tenancy Coffee plants	Private Private
B. Outcomes Chapeos/clearance (2 per year) Transport, Stock, Consultancy, Industrial processes, Others. Total	 $ 160.00 / year (£8.20/year) $ 0.266 / Kg. Café **cereza** $ 465.00 / ha (£23.84) $625.00 / ha / year (£32.02)
C. Incomes Value of the production (Typica and Robusta) Total	 $ 1.17 Kg **cereza** (£0.0585) 1,750 kg / ha $ 2,047.50 / ha / year (£102.35)
D. Net profit Species Typica and Robusta **Total**	**Ratio Benefit/Cost** $0.904 kg **cereza** (£0.04635) $1,582.00 / ha / year (£81.12)

The total ratio benefit/cost in TCS and RCS are very similar (Table 3.9), but what makes the final difference is the amount and quality of coffee production, about 50% more of profit in TCS than in RCS. The use and management of woody trees in both systems was the same in total annual profits.

Table 3.9 Ratio Benefit /Cost

Coffee system	Ratio B/C
RCS	
Coffee	$1,582.00 / ha / year (£81.12)
Trees	$ 14,350.00 to $ 16,750.00 / year
	£ 717.50 to £ 837.50 / year
Palms	$2,452.00 - £122.60
Total	**$18,386.00 / £942.87 to £961.22/ha /year**
TCS	
Coffee	$ 2,486.50 / ha / year (£127.48)
Trees	$ 14,350.00 to $ 16,750.00 / year
	£ 717.50 to £ 837.50 / year
Total	**$16,836.50 / £863.41 to £986.48/ha /year**

It is important to note that during this phase of the production, because the lack of means of transport and possibilities of commercialization, the farmer is just able to sell their production to intermediates ("coyotes") who will re-sell these products in the cities or companies obtaining for them the best profit during all the production chain.

Fig. 3.4 Sugar cane production in tropical forest in San Miguel, Veracruz.

3.4 Discussion

The importance of the management of the traditional and rustic coffee systems is based specially in their sustainability, conservation of resources and biodiversity characteristics (Moguel and Toledo, 1999), in México, some of the most important coffee production zones are in important bio-geographic and ecological zones, where tropical and temperate components meet, and in which 60 to 70 % of these areas are under a traditional and rustic way of management (INEGI, 2005).

Agroforestry has been developed as a an option for the management and conservation of the natural resources in the tropics that are quickly being degraded, mainly through the management of traditional crops and use of native trees which are mixed with crops as coffee and cacao (Somarriba, 1994). The use of high diversities of tree species and complex tree structure are considered important for the conservation of biodiversity (Perfecto et al., 1996, 2003) and soil (Nair, 1989).

As part of this thesis, an agroforestry characterization of the traditional coffee (TCS), rustic coffee system (RCS) and the altered subperenial medium forest (Selva mediana subperennifolia, Rzedowski, 1978) was carried out in San Miguel community on the Atoyac Mountain Range, in the state of Veracruz, México.

The TCS was composed of 15 tree species, whereas the RCS per 58 and the Spmf by 66 species. Of the tree canopy species excel those of timber, which are conserved mainly because of their commercial value as timber and fuel, examples of these are *Dipholis minutiflora, Cordia alliodora, Cedrela odorata* and *Sickingia macrophilla*, and others non-timber species like some fruit trees (mainly *Citrus* sp, *Mangifera indica*, and *Sapota mamey*) and palms.

The socio-economic analysis for these systems showed that the TCS characterized, manage the lowest tree species diversity but it has the greater economic remuneration because of the sale of the coffee, citric species and timber and fuel canopy tree species, mainly *Robinsonella mirandae*, *Dipholis minutiflora*, and *Mastichodendron capirii*.

For the RCS, the tree species diversity was higher but the economic remuneration is about the same as TCS, with less quantities of coffee to sell in the market but other products such as palms instead of coffee. In Spmf many of the tree canopy species have a commercial value as timber and fuel, are being illegally felled and sold to the market in the area and even to other states in the country.

The RCS agrisilvicultural system display an arrangement of the components as multilayer and multi-species with not organized and dense plant associations, the TCS have an arrangement of the components in essentially three layers and with 5 principal species only, with sparse plant associations and not organized arrangements. As far as its socio-economic characteristics, the RCS presents a high species diversity and characteristics of a subsistence system or low product commercialization, Through the use of coffee species as "Robusta" (*Coffea canephora*), palms and other products for self-consumption (medicinal plants, fruits and as well trees for construction and fuel), which are fundamentally native species.

The TCS and RCS are considered as intermediate socio-economical AF systems where the products sold in the market cover the basic needs of a family and are produced in small plots of land, usually these systems are based in coffee, cacao and coconut (Lundgren, 1982, Beer et al., 1998). As it was already described for both systems, the use of agro-chemicals is null and the agricultural labours minimal, reduced just to a couple of clearings and a pruning a year.

Probably the RCS could be a good option for the conservation of the natural resources and native tree species of the Spmf, although as an economic option it can be just as a self-subsystem production, probably a good option would be to increase the use of non forest products as the preservation and production of palms (*Chamaedorea* spp.) that are naturally grow in the native forest. In the case of the TCS, the economic profit is slightly higher than in the RCS, when obtaining timber and coffee products. The timber is mainly focus to the management of *Mastichodendron capirii* that can be used for construction, furniture industry and as fuel. Other tree species that are used in a smaller percentage, as *Dipholis minutiflora,* and *Cordia alliodora* can obtain better prices in the market, but they have been depleted faster in this type of systems and in the native forest as well.

3.5 Conclusions

The biophysical and ecological characteristics of the Atoyac Mountain Range turn out to be optimal for the development and culture of coffee. The RCS, which has been practiced in a traditional way already for almost 200 years, is now considered as part of the cultural identity of the region and a way of living for the native people of the region.

The association of the coffee with the multiple purposes trees, haven't showed any significant competition between the crop and ecosystems components, although the management of the ecosystems not always is sustainable and the use of the woody trees is increasing because of the economical crisis and the emigration of productive manpower towards the great cities and the United States of America.

About the tree component it is possible to conclude that according to the inventory and sampling realized in the studied parcels, there exists a tendency to the depletion of certain timber species in both RCS and TCS and the areas of disturbed Spmf as well, some of these species are *Cedrela odorata* and *Juglans* sp., as well as to a process of intensive use and felling of species as *Dipholis minutiflora, Cordia alliodora, Pithecellobium arboreum, Bernoulia flammea* and "Zopilote", which are commercialized for the elaboration of transport structures and construction of houses.

This type of selective cutting is bringing a change on the species composition of the systems with changes of Spmf to species of secondary vegetation, which contains a higher number of soft wood and faster growth species but with smaller commercial value as a timber, these species can solely be used as combustible and natural fences in some cases, such as *Bursera simaruba*, *Cecropia obtusifolia*, *Heliocarpus appendiculatus* and *Spondias mombin*.

The system nevertheless displays an efficient use of the external consumptions, with a suitable cycling of nutrients and good humidity and soil conservation, besides conserving some important tree species as *Robinsonella mirandae*, *Brosimum alicastrum*, *Astronium graveolens* and *Vatairea lundelii*.

The changes already done on the canopy species of the TCS about 30 or 40 years ago had some effects about the lumber of species in the canopy and the production of products such as coffee, wood, and fruits which have increased in some ways the economical inputs of the farmers. The use of *Mastichodendron capirii* and other woody species is being restricted to some trees every year because of their use as shadow, but the income is less than that of the RCS. The average production of coffee is slightly higher than RCS but it seems that the changes in the ecological conditions of the litter production and soil will be worth in a future due to the lack of protection for the wind and rain erosion as well for the leaching of soil and nutrients in the steep areas.

3.6 Recommendations

From the ecological point of view, it is important to conserve the characteristics of the rustic coffee system and the endemic and native species that are conserve on them, the diversity of the canopy tree species helps to maintain as well a high diversity of epiphyte plants, insect and animal species native from the tropical forest and the agroforestry systems are a good alternative to conservation and sustainable management of the resources in these ecosystems but the government policies and the abandonment of the traditional coffee plantations are leading to irreversible changes in the composition and structure of the native vegetation.

From the economical point of view, the RCS can be a good production system when is managed on sustainable terms, producing organic products which can be sold in an accurate market, some examples of it exists already in other coffee productive states as Chiapas and Oaxaca in México.

About the TCS, it can be a reliable system based but is based in the management of mainly two or three types of products, coffee, timber and in some cases fruits as some citric species. The diversity has been affected with the introduction of shade tree species as *Cecropia obtusifolia* and *Inga* spp, and the use without replacement of woody species as *Cordia alliodora, Dipholis minutiflora* and the use of *Mastichodendron capirii* instead of other native species.

Chapter 4 Canopy tree species composition in Traditional (TCS) and Rustic Coffee systems (RCS) and Subperennial medium forest (Spmf)

4.1 Introduction

Plant biomass represents the principal storage of nutrients in agricultural and natural systems and litter inputs are the major source of nutrients in tropical and in other terrestrial ecosystems (Swift et al., 1979; Jaramillo and Sanford, 1995). The amount, pattern and quality of the litter can be determinant in nutrient cycling and availability in the soil; these factors can be altered by anthropogenic effects such as conversion to agriculture, or as in this study, by incorporating of a forest canopy into an agricultural production area.

Some tropical vegetation responds to climatic seasonality in which trees shed their leaves in a response to drought (Holbrook et al., 1995) or winds, but the timing is mainly regulated by precipitation and temperature. The plant species can be a determining factor for nutrient cycling in many ways such as litter quality, litter productivity, nutrient uptake and loss, species interactions and associations with the colonies of decomposer organisms. In some terrestrial ecosystems more than 90% of the net above ground primary productivity is recycled in the form of litterfall and roots and constitutes the major source of resources for soil decomposer colonies (Swift et al., 1979).

Usually the feedback between tree species is considered to be positive for patterns of nutrient cycling and can reduce nutrient availability in poor environments or enhancing nutrient availability in nutrient rich environments, according to the quality of the plant litter (Hobbie, 1992, 2000).

4.1.2 Justification

The role of the tree components in the canopy structure and composition in coffee systems is important because of their potential to retain biodiversity and because they are the main source of replenishment of nutrient to the soil. The objective of this chapter is to present information about the canopy species diversity in rustic (RCS)

and traditional (TCS) coffee systems as well from the canopy of Sub-perennial medium forest (Spmf) and to analyze the species composition in each system. The data produced was afterward utilized for the further chapters in this thesis.

4.2 Materials and methods

Sampling

A total of 34 plots in traditional (TCS) and rustic coffee systems (RCS), and 30 for the semi-evergreen tropical forest (Spmf) with little disturbances were defined, nine were randomly selected: three for each system (See Chapter 2). Each sampling unit had a total surface of 1000 m^2 (20×50 m), and a tree inventory in which every tree (dbh≥10 cm) was recorded and were taxonomically identified (Beer, 1984) and localized with GPS (Garmin 2000) (Annex 1).

4.2.1 Coffee plantations

Based on the studies by Acevedo (1988) and Moguel and Toledo (1999) and the research done in the study zone (Bucio-Alanis and Colpos, 2001; Villavicencio, 2002; Villavicencio and Váldez-Hernández, 2003;), plots corresponding to TCS, RCS and Spmf where randomly chosen, three of each system. The physical attributes recorded for each system were: canopy structure (height, dbh, basal diameter (bd), vertical and horizontal arrangement, time arrangement per system component (coffee, shade trees, palms), species origin and use (Beer, 1984).

4.2.2 Floristic composition and appearance

Species- Area curve

A species-area curve was developed from the species sampled in the TCS, RCS and Spmf. The curve usually rises quickly initially because the first samplings reveal many new species, but subsequently, the curve levels stabilizes, because only a few more new species are found in the sampling (Greig-Smith, 1983, 1986). The collected tree canopy species were taxonomically identified with the aid of the research

literature on the flora of the Mountain range of Atoyac in Veracruz by Gómez-Pompa and Nevling (1970), Chiang (1970), Gómez-Pompa (1978), Acevedo (1988), Pennington and Sarukhán (1998), and Villavicencio (2002), with the aid of local people for the common names and uses of the tree component.

4.2.3 Shannon diversity index (H')

The Shannon index H' (Shannon and Weaver, 1949), is one of the most used in agroforestry (Somarriba, 2000) and its formula and it is calculated as follows (Magurran, 1988):

$H' = \Sigma\, Spi \ln pi$

Where: pi = Proportion (or relative abundance) of each species in the population

The Maximum diversity (H'max) can be calculated like:

$H'max = \ln S$ where: S = total number of species

And the Eveness is obtained by means of:

$$E = \frac{H'}{\sum \ln S} = -pi \ln pi$$

In order to know the significant differences for the diversity of tree species between the rustic RCS, TCS and Spmf, the method of Hutcheson was used (Magurran, 1988), to calculate "t" as follows:

$$t = \frac{H'_1 - H'_2}{(VarH'_1 + VarH'_2)^{1/2}}$$ Where:

H'_1 = Shannon Diversity index value (RCS, TCS);
H'_2 = Shannon Diversity index value Spmf;
Var H'_1 = Shannon Diversity index value variance (RCS, TCS);

Var H'_2 = Shannon Diversity index value variance Spmf.

And degrees of freedom using:

$$df = \frac{(VarH'_1 + VarH'_2)^2}{((VarH'_1)^2 / N_1) + (VarH'_2)^2 / N_2))}$$

The variance for H' in each system was determined using the formula:

$$Var = \frac{(\sum pi(\ln pi)^2 - (\sum pi \ln pi)^2}{N} - \frac{S-1}{2N^2}$$

4.2.4 Jaccard Index of similarity (Cj)

The Index of Jaccard (Cj) is based on Absence-Presence between the number of species in each community and the total number of species (Stiling, 1999), and is calculated as follows:

$$Cj = \frac{C}{A} + B - C$$

Where: C = Number of species in common

A = total number of species found in the unit sampling A

B = total number of species found in the unit sampling B

4.3 Results and discussion

4.3.1 Species composition and physiognomy

The results obtained from the tree canopy species inventories are: a total of 82 tree canopy species in the study sites: 15 corresponding to TCS, 62 to RCS and 66 to Spmf. From the total of 82 recorded species, nine were not botanically identified in this study. The species correspond to 37 botanical families of which the Fabaceae is dominant with a total of 13 species. For each species their scientific name, common name and uses were recorded (Table 4.1).

Table 4.1 Tree canopy species inventory in TCS, RCS and Spmf in San Miguel, Veracruz. México.

Species	Cientific name	Family	Uses
Aguacate	*Persea americana* var. Drymifolia Blake	Lauraceae	1,2
Aguacatillo	*Persea gratísima* Gaertn	Lauraceae	1,2
Amargoso	*Vatairea lundeli* (Standi.) Killip	Fabaceae	6
Anona	*Annona muricata* L.	Annonaceae	1
Balsamo	*Myroxylon balsamum* L. (Harms)	Fabaceae	2
Cacahuapastle	*Hamelia patens* Jacq.	Rubiaceae	7
Cacao	*Virola guatemaltensis* (Hemsl). Warb.	Myristicaceae	2,4
Canilla	*Cupania dentata* Moc. et Sessé ex D.C.	Fabaceae	7
Cañamazo	*Pithecellobium arboreum* L.	Fabaceae	2,3
Carbonero		n.d.	2,3
Carne asada	*Roupala montana* Aubl.	Proteaceae	2,3,4
Cedrillo	*Trichilia hirta* P. Browne	Myristicaceae	6
Cedro	*Cedrela odorata* L.	Meliaceae	4
Cedro Macho	*Cedrela sp.*	Meliaceae	2,6
Cola de lagarto	*Zanthoxylum sp.*	Rutaceae	7
Comalillo	*Coccoloba hirtela.* P Browne	Compositae	3
Coralillo		n.d.	7
Cordoncillo	*Piper hispidum* Sw.	Piperaceae	7
Cozahuico	*Mastichodendron capirii*	Sapotaceae	2,4
Cucharilla	*Trichilia havanensis.* Jacq.	Meliaceae	7
Chinene	*Persea schiedeana* Ness	Lauraceae	6
Chiquite	*Senna spectabilis* (DC) H.S. Irwin & Barneby	Fabaceae	7
Escobilla	*Sida acuta* Burm F.	Malvaceae	7
Frijolillo	*Lonchocarpus rugosus Benth.*	Fabaceae	2
Gasparito	*Erythrina Americana* (Dryander) Mill	Fabaceae	7
Gateado	*Astronium graveolens*	Anacardiaceae	7
Granicillo		n.d	7
Guacalillo		n.d.	7
Guacima	*Guazuma ulmifolia* Lam.	Sterculiaceae	7
Guajillo	*Albizzia purpusii* Britton & Rose	Mimosaceae	7
Guanacaste	*Enterolobium cyclocarpum* (Jacq) Griseb	Fabaceae	2,3
Guarumbo	*Cecropia obtusifolia* Bertol.	Urticaceae	6
Guayabillo	*Malpighia glabra* L.	Malpighiaceae	7
Gusanillo	*Vernonia patens* Kunth	Asteraceae	1,2
Hediondillo	*Cestrum nocturnum* Ruiz & Pavon.	Solanaceae	6
Higuera	*Ficus tecolutensis* Lieb. Miq .	Moraceae	2,3
Higuerilla	*Ficus* sp.	Moraceae	2,3
Hoja María		n.d.	7
Huevo de Toro	*Stemmadenia donnell-smithii* (Rose in Donn. Sm.) Woodson.	Apocynaceae	7
Izcoahuite		n.d.	7

Jabonosa	*Sapindus saponaria* L.	Sapindaceae	7
Jobo	*Spondias mombin* L.	Anacardiaceae	7
Jonote	*Heliocarpus appendiculatus* Turcz.	Tiliaceae	7
Jonote Real	*Heliocarpus donnell-smithii* Rose.	Tiliaceae	7
Lechudo	*Pseudolmedia oxyphyllaria* Donn. Sm.	Moraceae	7
Mameicillo	*Sapium lateriflorum* Hemsl	Euphorbiaceae	7
Mango	*Mangifera indica* L.	Anacardiaceae	1,2,6
Manzanillo	*Robinsonella mirandae* Gomez-Pompa	Malvaceae	2,3,4,6
Manzanita	*Bellucia grossularoides* (L.) Triana	Melastomataceae	7
Molinillo	*Quararibea yunckeri* Standl. Alverson	Bombaceae	7
Naranjo	*Citrus sinensis* Osbeck	Rutaceae	1
Naranjo Malto	*Citrus reticulata* L.	Rutaceae	1
Nazareno	*Sickingia salvadorensis* Standl.	Rubiaceae	2,4
Nogal	*Juglans sp.*	Juglandaceae	4
Ojoche	*Brosimum alicastrum* (Sw.)	Moraceae	2,3
Palo de agua	*Irisine nigra* Uline & W.L. Bray	Amaranthaceae	7
Palo mulato	*Bursera simaruba* (L) Sarg.	Burseraceae	7
Paticabra	*Bauhinia divaricata* L.	Fabaceae	7
Peinecillo	*Aphanante monoica* (Hemsl.) J. F. Leroy	Sapotaceae	7
Pimienta	*Pimenta dioica* (L) Mer.	Myrtaceae	7
Pixtle	*Prunus brachyobothya* Zucc.	Rosaceae	1,2,3,6
Platanillo	*Bernoullia flamea* Oliv.	Bombacaceae	2,3,6
Pochota	*Hura polyandra* Baill.	Euphorbiaceae	7
Quina	*Exostema mexicana* Gray.	Rubiaceae	5
Roble	*Tebebuia roseae* (Bertol.) DC	Bignoniaceae	4
Rosadillo	*Mirandaceltis monoica* (Hemsley) Sharp	Ulmaceae	2
Sangregao	*Croton draco* Schltdl. & Cham.	Euphorbiaceae	5
Siete cueros	*Cordia diversifolia* Pav. Ex A DC.	Boraginaceae	7
Sopa de pan	*Alchornea latifolia* Sw.	Euphorbiaceae	6
Tabaquillo	*Lippia strigulosa* M. Martens & Geleotti	Verbenaceae	7
Tempesquistle	*Dipholis minutiflora* Pittier	Sapotaceae	4
Tempisque	*Syderoxylon capiri palmeri* (Rose)	Sapotaceae	4
Tepeguaje	*Lysiloma* sp.	Fabaceae	7
Vainillo	*Inga vera* Willd.	Fabaceae	6
Vainillo Real	*Inga paterno* Harms.	Fabaceae	6
Vainillo tejonero	*Inga brevipedicellata* Harms.	Fabaceae	6
Ventosidad	*Croton officinalis* (Klotzsch) Alston	Euphorbiaceae	2,5,6
Volador	*Zuelania guidonia* (Sw) Britton & Millsp.	Flacourtiaceae	2,6
Xochicuahuitl	*Cordia alliodora* (Ruiz & Pavon) Oken	Boraginaceae	4
Zapotillo	*Bunchosia lanceolata* Turcz.	Malphigiaceae	7
Zopilote		n.d.	2,4
Zapote mamey	*Malinkara sapota* L. V. Rogen	Sapotaceae	

Note: Uses it refers to: 1. Food, 2. Construction, 3. Truck structures, 4. Wood (for construction and fuel), 5. Medicinal, 6. Shade, 7. Not defined. N.d.: non identified species.

A species- area curve was developed for the sampling sites (Fig 4.1). The results of the tree canopy inventory showed that the 62 species recorded in the RCS is a intermediate value in a comparison with the results reported in Costa Rica, between 19 and 49 species (Llanderal, 1998), and El Salvador with between 92 and 136 species recorded, Somarriba et al. (2004).

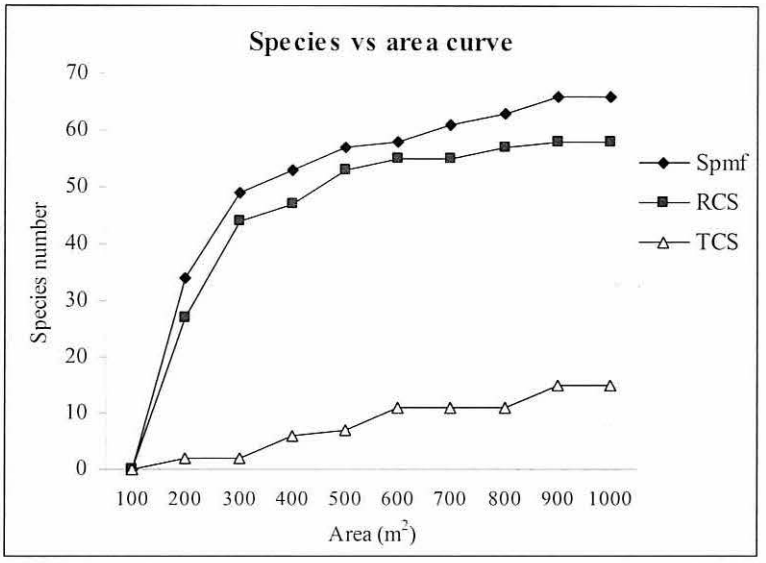


Fig. 4.1 Species-Area curve in TCS, RCS and Spmf

Note: Spmf: Subperennial forest; RCS: Rustic coffee system; TCS: Tradicional coffee system

The dominant species in the three systems canopies are mostly representative of the native and secondary subperennial medium forest; TCS showed the lowest number of species including some native but mostly introduced for example *Inga* sp.

The species recorded corresponded to 37 families. The results are similar to the studies done in Spmf in Veracruz by Castillo et al., (2003) where they found that the Fabaceae family was the most representative in number of species followed by Euphorbiaceae, Asteraceae and Rubiaceae. In this study the leading families were Fabaceae > Euphorbiaceae > Sapotaceae > Moraceae > Rutaceae, Rubiaceae, Lauraceae and Meliaceae and others (Table 4.2).

Table 4.2 Families species composition in TCS, RCS and Spmf

Botanical families	Species number
Fabaceae	13
Euphorbiaceae	5
Sapotaceae	5
Moraceae	4
Lauraceae	3
Meliaceae	3
Rubiaceae	3
Rutaceae	3
Anacardiaceae	2
Boraginaceae	2
Malphigiaceae	2
Malvaceae	2
Myristicaceae	2
Tiliaceae	2
Bombaceae	2
Amaranthaceae, Annonaceae, Apocynaceae, Asteraceae, Bignoniaceae, Burseraceae, Compositae, Flacourtiaceae, Juglandaceae, Malvaceae, Melastomataceae, Mimosaceae, Myrtaceae, Piperaceae, Proteaceae, Rosaceae, Sapindaceae, Solanaceae, Sterculiaceae Ulmaceae, Urticaceae, Verbenaceae	1

Gómez-Pompa (1978), noted that the most representative family in the Spmf and Sub perennial high forest was Fabaceae, but it could indicate an alteration of secondary vegetation as well, because of their fast growth habit and adaptability in sites poor in nutrient. *Inga* spp are an important component in many coffee systems in Central America and México, as has been reported for Jiménez-Avila (1979) and Marten and Sancholuz (1981).

4.3.1.1 Subperennial medium forest species composition

Mainly native tree species dominated the Spmf, some of these being: *Cedrela odorata*, *Brosimum alicastrum*, *Bursera simaruba*, *Roupala montana*, *Sideroxylon capiri*, *Trichilia hirta*, *Robinsonella mirandae*, *Juglans* sp. amongst others, and some typical species of secondary vegetation were indicated by *Trichilia havanensis*, *Piper hispidum*, *Bauhinia divaricata* and *Cupania dentata*. A total of 66 canopy species were recorded as part of the species inventory. The secondary vegetation was represented by a mix of native species of different successional stages, and some

indicative species which indicate alteration in the native vegetation as *Trichilia havanensis, Cupania dentata, Piper hispidum* and *Bauhinia divaricata.*

These species have a fast growth in the lower and medium vegetation strata as part of their survival strategies and usually appear in patches of clear vegetation or where trees have been removed and belong to Fabaceae family which is an important component of native vegetation but can also represent disturbed vegetation (Chiang, 1970; Gómez-Pompa, 1978, 1999). Other species noted to have a high presence were *Bursera simaruba*, which has the same fast growth habits than the species of the medium and lower strata. The average height of the tree canopy component in Spmf was 25 m. Some frequent representative species are *Dipholis minutiflora, Robinsonella mirandae, Ficus tecolutensis, Croton officinalis* and *Erythrina americana* and *Ficus sp.*

4.3.1.2 Rustic coffee system species composition

The RCS had a similar species composition to Spmf, but with more exotic species such as *Mangifera indica* and *Citrus sinensis.* This system is represented mainly by native species such as *Piper hispidum, Robinsonella mirandae, Dipholis minutiflora, Sideroxylon capiri* and *Croton officinalis*, and an important number of species that are recognized as typical of disturbed zones in the native forest such as *Cupania dentata, Bauhinia divaricata, Erythrina americana* and *Hamelia patens* (Gomez-Pompa, 1978). Some species form the lower and medium strata have an important presence in this system, these are *Inga* spp, *Piper hispidum* and *Cecropia obtusifolia,* both introduced as part of the coffee growing government policies. The exotic species *Citrus* sp and *Mangifera indica* besides the *Cordia alliodora, Cedrela odorata, Persea Americana* and *Inga* spp, are common shade species that commonly are part of the canopies in coffee plantations in the Central American coffee zones (Somarriba, 2004).

4.3.1.3 Traditional coffee system species composition

The use of shade tree species as canopy in these coffee systems has reduced the number of the native canopy species to just 15. The most representative species are:

Inga spp (*brevipadicellata, paterno* and *vera*); *Cecropia obtusifolia, Astronium graveolens, Spondias mombin* and some timber species such as *Mastichodendron capirii, Cedrela odorata, Dipholis minutiflora* and *Cordia alliodora*. In some areas most of the shade tree canopy component is composed mainly with *Mastichodendron capirii* which is used for fuel and for some construction purposes.

Fig. 4.2 Subperennial medium forest in San Miguel, Veracruz, México.

Fig. 4.3 Traditional Coffee System (Coffee-Banana-*Cedrela odorata*).

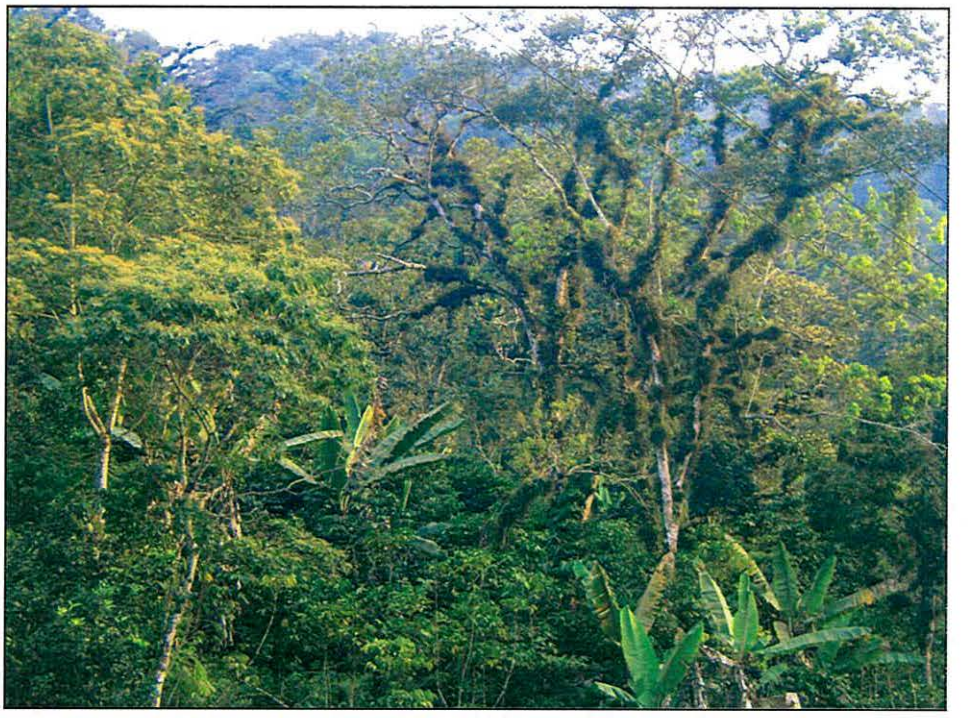


Fig. 4.4 Rustic Coffee systems in San Miguel, Veracruz. México.

4.3.1.4 Canopy structure in TCS, RCS and Spmf

Differences in the canopy height and tree component density were obvious in TCS with respect to the other systems (10 to 15 m. height Table 4.3), but between Spmf and RCS (4.4) the canopy height was similar, around 20 to 25 m. height respectively.

Table 4.3 Arrangement of components TCS: Trees - Coffee.

Component	Leaf type	Vertical arrangement (m)	Horizontal arrangement	Temporality
Trees	Evergreen + deciduous	0–20 m Multistratified	Mix - sparse	Simultaneous - Permanent
Coffee plants	Evergreen	One main strata var. Typica with a few Robusta 5 to 7 m.	Mix - Sparse	Simultaneous - Permanent

Table 4.4 Arrangement of components Spmf and RCS: Trees - Coffee – Palms.

Component	Leaf type	Vertical arrangement (m)	Horizontal arrangement	Temporality
Trees	Evergreen + deciduous	0–25 m Multistratified	Mix - dense	Simultaneous
Coffee plants (in RCS)	Evergreen	Two strata var. Typica & Robusta 5 to 7 m.	Mix - dense	Simultaneous - Permanent
Palms	Semi-Evergreen	At forest floor level to 1.5 m.	Mix - sparse	Simultaneous - Permanent

4.3.1.5 Index of Similarity

The Jaccard coefficient values applied to the systems of Spmf and RCS were 0.61, or 61% of similarity between communities meanwhile the similarities between Spmf vs TCS and TCS vs RCS were 12.5 and 11.86 % respectively (Table 4.5).

Table 4.5 Coefficient of jaccard for TCS, RCS and Spmf

System	Coefficient of Jaccard	% Similarity
Spmf vs RCS	**0.6103**	**61%**
TCS vs RCS	**0.1186**	**11.86 %**
TCS vs Spmf	**0.125**	**12.5 %**

Tree canopy species unique for each system were recorded during the plot sampling species, of these, six were not botanically identified, Carne asada and Granicillo for the RCS, "Cacahuapaxtle" and "Chinene" for TCS and "Guacalillo" and "Hoja Maria" for the Spmf. Exotic species were representative in the TCS and native species from the low and intermediate canopy height in RCS and Spmf were representative of these systems. *Cedrela odorata, Enterolobium cyclocarpum, Heliocarpus donnell-smithii* and *Mirandaceltis monoica* in Spmf are valuable woody species that are conserved for economical reasons mainly as well the *Citrus* spp, *Malinkara sapota, Mangifera indica, Inga paterno* and "Chinene" in the TCS. The species recorded in the RCS are part of the low and intermediate canopy layers of the secondary forest and some are use as medicinal plants (*Croton draco, Exostema mexicana, Irisine nigra*) or as a shade for the coffee crops (Table 4.6)

Table 4.6 Canopy species not shared between systems

RCS	TCS	Spmf
Albizzia purpusii	Cacahuapaxtle*	*Cedrela* sp.
Alchornea latifolia	Chinene*	*Croton officinalis*
Trema micantra	*Citrus reticulata*	*Enterolobium cyclocarpum*
Carne asada*	*Citrus sinensis*	Guacalillo*
Croton draco	*Malinkara sapota*	*Heliocarpus donnell-smithii*
Exostema mexicanum	*Mangifera indica*	Hoja María*
Granicillo*	*Inga paterno*	*Inga brevipedicellata*
Guazuma ulmifolia		*Isochilus linearis*
Hamelia patens		*Juglans* sp.
Hura polyandra		*Mirandaceltis monoica*
Irisine nigra		*Persea schiedeana*
Pithecellobium arboreum		*Prunus brachyobotrya*
Senna spectabilis		*Roupala montana*
Stemmadenia donnell-smithii		*Sapindus saponaria*
Zanthoxylum sp.		*Tabebuia roseae*
		Trichilia havanensis
		Trichilia hirta
		Vernonia patens
		Virola guatemaltensis

*=Not botanically identified species in this study.

4.3.1.6 Shannon diversity index

The highest values for H' were obtained in the Spmf and RCS (3.564 and 3.348 respectively) and the lowest in the TCS (0.81) which indicates that at least in number of species, the diversity between RCS and Spmf is very close but the H' of the TCS very low in comparision with the other two systems (Table 4.7).

Table 4.7 Shannon index (H'), Evenness and Variance values

System	H'	Evenness	Variance
TCS	0.81	0.1658	6.6841
RCS	3.348	0.5856	0.002762
Spmf	3.564	0.7299	0.002941

The results indicate a higher Shannon index (H') in the Spmf and RCS than in the TCS. This index in RCS is slightly higher than the ones measured in Central America in other shade coffee systems (Table 4.8).

Table 4.8 Shannon diversity index in canopy species of *Coffea arabica* in traditional and rustic plantations in Central America and México.

	Turrialba Costa Rica (n=29)	Carazo Nicaragua (n=36)	Esteli Nicaragua (n=31)	Santa Ana El Salvador (n=40)	This study México (n=6)
H´	1.57	2.06	2.85	3.08	3.34

Source: Somarriba, 2004.

There is a more equitable distribution between species in the forest than in the Rustic coffee system, where the disturbance is higher because of the cultivation of the coffee. Homogeneity of variance test for the systems (Steel and Torrie, 1986) showed that it was not significant for the Spmf and RCS but it was in the TCS ($p \geq 0.05$). The values obtained for the Spmf are common for this type of vegetation as has been demonstrated by Saï and Manesh, (1986); Kumar, (1990); and Phatak et al., (1993), on their respective studies.

4.4 Discussion

The anthropogenic disturbance of the native vegetation has led to big changes in the composition and structure of the forest and in some cases has been transformed because the agricultural management in a wide range of agro-ecosystems, agroforestry systems and altered native vegetation into secondary forests at different stages of succession. Some of the native undisturbed vegetation areas in the zone of the mountain range of Atoyac of difficult access are developed in rocky karstic areas. Some of the native species it is possible to find are *Malinkara sapota, Brosimum alicastrum, Aphananthe monoica* and *Astronium graveolens*, but the extraction of some other woody valuable species such as *Robinsonella mirandae, Cedrela odorata* and *Mastichodendron capirii*, the influence of the agricultural activities and the legal and illegal felling has lead to major changes in the composition of vegetation and the advance of the secondary vegetation. Such vegetation is characterized by abundance in the lower strata of herbs and bushes and a presence of more species from the families Fabaceae, Poaceae and Astaraceae which are indicators of secondary vegetal communities (Gómez-Pompa, 1978).

Other important characteristic in the native vegetation was the presence of some endemic species from the lower strata, such as palm species (*Chamaedorea* spp.) and *Yucca* sp., which are very sensitive to the perturbations from the agricultural activities but are still conserved in these ecosystems.

In the native vegetation or Spmf, the over exploitation of some woody species and the influence of agriculture in the native vegetation (Spmf) in the Atoyac mountain range has resulted in changes in the canopy species composition and a major influence of the secondary vegetation in the zone. Other introduced species such as *Citrus sinensis, Citrus limon, Mangifera indica, Coffea arabica, Cecropia obtusifolia* and *Inga* spp. are common.

In the traditional coffee plantations, some of the tree forest components have been substituted by and exotic species as *Mangifera indica, Musa paradisiaca, Citrus limon* and *Citrus sinensis* and others but in San Miguel apart from these species; *Mastichodendron capirii* has been substituted mainly for introduced species such as

Inga spp, *Cecropia obtusifolia* which can be a faster economical income source or as a source of fuel.

The three systems differ in their structure, species composition and species diversity. The RCS is composed of three different types of vegetation; these are from the native forest, from secondary vegetation and exotic species. The introduction of species such as *Citrus* spp and *Inga* spp., have brought some important changes to the canopy structure as well. The H' diversity index is very close to the ones showed by other studies in Central America (Table 4.8).

In the TCS only 15 species were recorded; these species usually have some economic value such as *Mastichodendron capirii*, which is used for fuel and in construction. Other species such as *Dipholis minutiflora* and *Cordia alliodora* have an important economic value in the timber market of the region. *Cecropia obtusifolia* and *Inga* spp are species that were introduced in the region about 30 years ago and their use is mainly as shade for the crop, these species have a low economic benefit but are conserved because of their shade value.

The tree species canopy composition in Spmf conserve more native tree species such as *Malinkara sapota, Aphanante monoica, Brosimum alicastrum, Syderoxylon capiri* and *Astronium graveolens*, but it is starting to show some changes in species composition with a major presence of species belonging to the Fabaceae family which can be indicative of alteration in native vegetation or secondary vegetation. Other families that are representative of altered or secondary vegetation are Astaraceae and Poaceae (Gómez-Pompa, 1978) but those have a small presence in the study areas.

Some of the species that are important because of their endemic status are *Bauhinia* sp., *Bursera* spp., *Inga* spp., *Quararibea yunckeri*, *Astronium graveolens*, *Mastichodendron capirii* and *Robinsonella mirandae* (Gómez-Pompa, 1966,1978; Fryxell, 1992; Ibarra-Manrriquez & Sinaca, 1995) and the palm *Chamaedorae sartorii* and *Chamaedorea tepejilote* (SEMARNAT, 2005)

4.5 Conclusion

It must be considered that the over exploitation of woody species such as *Roupala montana, Cedrela odorata, Dipholis minutiflora* and *Cordia alliodora* is bringing about a change in the systems composition and structure in favour of species considered as "soft wood" as *Heliocarpus appendiculatus, Bursera simaruba* and *Croton draco*, as well the predominance of species that form part of the lower and medium strata in the forest (*Cupania dentata, Piper hispidum and Bauhinia divaricata*), depending on the degree of management.

As a logical consequence of the changes in the canopy tree species composition, the standing leaf litter production was different in the systems, and the dominance of the Fabaceae family is an important factor in these changes.

Chapter 5 Leaf litter production, mass loss and decomposition rates in Traditional (TCS) and Rustic (RCS) coffee systems and Subperennial medium forest (Spmf).

5.1. Introduction

Primary production in tropical forests

In tropical regions with warm temperatures, high rates of humidity and abundant rainfall over at least one rain season (Jordan, 1971) such climatic factors determine the rates of decomposition of organic matter on the forest floor. During the dry season the growth of the plants restricted by the lack of moisture which inhibits photosynthesis resulting in a lower primary productivity in the ecosystem. The net primary production which includes wood material plus litter-fall is higher in wet tropical ecosystems then in any other terrestrial ecosystem. This high primary net productivity production in native tropical forests is fundamental for the reciclyng and storage of nutrients in the ecosystem.

Net Primary Production (NPP) is an important process in terrestrial ecosystems which provides the link between organic decomposition and the primary production processes; it is the most important route of transfer of energy within the ecosystem (Alvarez-Sánchez & Guevara, 1993). It is also the main route for nutrient cycling and re-cycling to the soil (Meentemeyer et al., 1982). NPP is distributed in four ways, some is stored as biomass (including roots) some is secreted as soluble organic matter, some is consumed by animals and insects and some is shed as plant litter and deposited on the forest floor. Large quantities of annual litterfall are characteristic of tropical ecosystems and specifically in evergreen and semi evegreen forests. Leaf litter quantity, quality and seasonality affect the heterogeneity of the litter layer, litter decomposition and subsequent nutrient cycling (Burghouts et al., 1992).

Litter decomposition process

Litter production and decomposition in any ecosystem are basic processes in ecosystem functioning and is a major determinant of the rate of nutrient cycling in most terrestrial ecosystems (Meetenmayer, 1978; Swift and Anderson, 1989; Aerts

and De Caluwe, 1997). Decomposition it is usually measured as mass loss through time and many studies has been conducted in different climates and vegetation types. Other factors have been considered in these studies such as the colonies of decomposer micro-organisms, CO_2 efflux, isotope fractionation and ^{13}C enrichment in soil profiles during the decomposition of soil organic matter (Bjorn & Comstedt, 2007).

The influence of the climate and litter quality has been studied in various terrestrial ecosystems (Meetenmayer, 1978; Aber et al., 1990; Vitousek et al., 1994; Aerts, 1997; Sanger et al., 1998; Moore et al., 1999; Almendros et al., 2000; Aber and Melillo, 2001).

The effect of litter quality, which is strongly influenced by tissue type on decomposition, is most pronounced during the first stages of decomposition (Trofymow et al., 2002). The climate as well, has an important effect on decomposition of organic matter in the forest floor and is responsible of the influence of the humidity and temperature important for the development of the colonies of decomposer micro-organisms and that affect directly the decomposition processes.

Climate is one of the three important factors that control the decomposition processes in the ecosystems (the other two are quality of the resource and colonies of decomposer micro-organisms), and it is considered to be the main factor in areas subjected to unfavourable weather conditions (Swift et al., 1979; Melillo et al., 1993; Couteaux et al., 1995; Bjorn and Comstedt, 2007; Zhou et al., 2008).

Most studies on decomposition in forests have focused on aboveground tree components, such as foliage (Proctor et al., 1983; Melillo et al., 1989; Sundarapandiam and Swamy, 1999), bark, branches, and wood (Harmon et al., 1995). Far fewer studies have examined the decomposition of roots, understorey herbs, shrubs, and moss, although these components may comprise a large proportion of the live biomass. For example, a large proportion of net primary productivity is allocated to fine roots in boreal forests (Agren et al., 1980; Grier et al., 1981; Keyes and Grier, 1981) where potentially more soil C comes from fine roots than aboveground biomass (Vogt et al., 1996).

In México, leaf-litter decomposition studies using the litterbags method or direct observation of mass loss has been studied in low deciduos forest (Martínez-Yrizar, 1980, 1984), tropical dry forest by Xuluc-Tolosa et al. (2003), arid zones (Montaña et al., 1988; Maya and Arriaga, 1996; Nuñez, 1998), temperate forest (Ezcurra and Becerra, 1987), pine-oak forest and grasslands (Montaña et al., 1988), evergreen tropical high forest (Alvarez-Sánchez and Guevara, 1993; León, 1994) and semi-evergreen tropical medium forest (León, 1994; Harmon et al., 1995).

5.1.1 Litter decomposition process

Factors that influence the litter decomposition process

The decomposition process mainly consists of three elements or groups of factors that are related, the physical-chemical environmental factors (soil and climate), the quality of the resource (Aerts, 1997) and a third that is regulated by these previous factors, the community of micro-organisms decomposers (Swift et al., 1979; Swift and Anderson, 1989).

Soil conditions and climate (Aerts, 1997) can cause the main variation in the chemical composition of plant tissues through determination of plant communities and species (Heal et al., 1997) and their major life form (annual, deciduous or evergreen perennial etc). The distribution of ecosystem types determined by the character of their vegetation is broadly correlated with climatic conditions (Swift et al., 1979). Environmental factors such as light (Rice and Bazzaz, 1989; Covelo and Gallardo, 2004), CO_2 (Cotrufo et al., 1995; Tuchman et al., 2003), temperature (Dury et al., 1998), ozone (Findlay et al., 1996) and soil nutrient status (Bryant et al., 1993; Marschner, 1995; Wait et al., 1998) also affect the biochemical composition of plant structures. The availability of nitrogen (N) alters the biochemical composition of plant tissues more than any other mineral nutrient (Marschner, 1995). The magnitude of a plant's response to external factors is pre-determined by its growth strategy (Cornelissen, 1996; Cornelissen et al., 1999) and genotype (Keinänen et al., 1999).

Temperature has an important effect in the decomposition process which increases exponentially with temperature; that is, for every 10°C rise in temperature,

decomposition increases by a factor of 2 (Jenny, 1994). Nevertheless, leaf decomposition in temperate climates does occur at a low rate during the winter months even under deep snow (Taylor and Jones, 1990). In humid climates where temperature and humidity is less constraining, the rate of decomposition depends mainly on the soil properties, humus and litterfall quality, unlike other latitudes where the litterfall decomposition depends on the climate as boreal regions and mediterranean climates (Swift et al., 1979).

Two basic processes are involved in decomposition: Comminution in which the litter is broken down to small pieces which can be chemically reduced by insects, small herbivores and other organisms, and in a second part of the same stage, micro-organisms like bacteria and fungi reduce even more the litter pieces of organic matter and are mineralized into basic organic molecules such as ammonium, phosphate, CO_2 + H_2O which can be available to plants, micro organisms or be leached out of the system. A second stage for the decomposition process is the catabolism which is the process that the litter is broken down into even smaller pieces as well but through chemical processes (Swift et al., 1979; Swift and Anderson, 1989; Aerts, 1997).

In this second stage leaching by water of the leaf litter constituents takes place and the litter suffers a nutrient "washing" of some nutrients such as N, P, and some phenols, which are influenced by the first stage of decomposition where mineralization and humification of lignin, cellulose and other compounds occurs. After some time, the lignin, phenols and tannins act as principal agents in the deceleration of the decomposition process, once the nutrients have been leached. Soil leaching downward of soluble compounds whose C and N are progressively mineralized or immobilized. Both processes are carried out by means of a succession of decomposer micro organisms like fungi and bacteria. The early stages of decomposition are strongly affected by the climate and the concentrations of soluble nutrients in water and structural carbohydrates in leaf-litter whereas the later stages of decomposition are influenced more by the lignin concentration (Berg, 2000).

The model most widely used to describe the decomposition process has been the single exponential model, usually the negative exponential (Jenny et al., 1949), and it has been the most used in studies in the tropics (Anderson and Swift, 1983; Gong and

Ong, 1983; Frangi and Lugo, 1985; Cuevas and Medina, 1988, Saldarriaga, 1994; Harmon et al., 1995; Songwe et al., 1995; Alvarez-Sánchez and Becerra, 1996; Landsberg and Gower, 1997). Theorically the litterfall is composed of a labile fraction that consists of sugars and proteins which rapidly decomposes and another fraction more recalcitrant which is composed mainly of lignin, phenols, celluloses and some hemi-celluloses that decompose more slowly (Binkley, 1986).

5.2 Materials and Methods

5.2.1 Study site and Experimental design

The research study zone is described in full in Chapter 3. The community of San Miguel is located in the Mountain range of Atoyac comprises of the Sierra Madre Oriental (Eastern mountain range) and it is in the region of great mountains in the central part of the state of Veracruz, it is located 42 km from the city of Cordoba, Veracruz, and it has an altitude ranging from 750 to 1,400 m. a. s. l., a humid warm climate type (A) C' (m) w'o (Köppen climatic Classification, modified by Garcia, 1987), The soils are classified as vertisols and rendzinas because their reddish coffee color and pH around 6.0 (FAO-UNESCO, 2007). The municipality of Amatlán de Los Reyes is located at 18°51′ and 96°55′ at 830 m. a. s. l., and with a total surface of 148.88 ha. It has an annual average precipitation of 2,500 mm and a dry season from November to May, and annual average temperature of 22.5° C.

Nine blocks (100 m^2 each), three representing the traditional coffee system (TCS), three for rustic coffee system (RCS) and three more subperennial medium forest (Spmf) were chosen at random in the community of San Miguel, Veracruz. (See Chapter 3 and Annex 1).

5.2.2. Leaf-litter production, sampling time and collection

Three litter traps were randomly placed in each of the study sites to collect the fresh fallen leaf litter material every 15 days during 12 calendar months from January to December 2006. The litter traps measured 1x1 m ($1m^2$) and were horizontally adjusted to a height from 50 to 70 cm from the forest floor (depending on the slope of

the terrain). After collection the material was processed by sifting out the non-leaf litter and it was free of obvious deformations or damages caused by micro-organisms, insects or animals it was cleaned manually and with distilled water and dried for 48 hours in an oven at 60°C (Palm and Rowland, 1997; Anderson and Ingram, 1989). After drying the material was weight and separated by the most representative and dominant species. Calculations of the total leaf-litter (Dry weight) production/ha per parcel, dominant and most representative species were completed.

5.2.3 Litterbags and decomposition rates

Leaf litter decomposition is most commonly measured using the litter bag technique. A known quantity of leaf litter is placed into a mesh bag which is then inserted into the litter layer of a forest floor. Bags are harvested at periodic intervals, dried and reweighed to determine the amount of mass lost. By incubating the leaves *in situ*, they are exposed to the normal fluctuations in temperature and moisture. The mesh bags allow smaller insects as well as micro-organisms access to the leaves.

Litterbags (10 X 10 cm) were made with a 1 mm mesh and in each, 10g dry weight of leaf litter was placed (252 in total). Different mixes were prepared with leaf litter of typical species components of the Subperennial medium forest (Spmf) and traditional (TCS) and rustic (RCS) coffee systems (Table 5.1). Seven series of four litterbags each were placed and retrieved during seven sampling intervals from day 1, to 11, 22, 44, 88, 176 and 352.

Table 5.1 Litterbag contents per system

TCS	RCS	Spmf
+Robinsonella mirandae	*+Robinsonella mirandae*	*+Robinsonella mirandae*
^Robinsonella mirandae/Coffea arabica	*^Robinsonella mirandae/Coffea arabica*	*^Robinsonella mirandae/Coffea arabica*
**Mastichodendron capirii*	**Piper hispidum*	**Croton officinalis*
Mix	Mix	Mix

Note: +Spmf typical species component; ^ *Robinsonella mirandae/Coffea arabica;* *Typical species per each system; Mix of the most representativee leaf litter species of each system (see Table 4.1.).

Leaflitter representative of the tree species of the plots randomly chosen, composed the material introduced in the litterbags to measure the decomposition "in situ". These materials consisted in percentages of some of the most representative species per plot and do not concide with the most productive species necessarely. *Robinsonella mirandae* is a native and dominant species present in all the systems and the mix of *Robinsonella mirandae/Coffea arabica* was intended to include the variability of the crop species in the decomposition process. *Mastichodendron capirii, Piper hispidum* and *Croton officinalis* represent the dominant species for each of the systems (TCS, RCS and Spmf respectively) and finally, a litterbag with a mix of the five most representative species for system was included to represent the variability in field.

Each of the series contained four litterbags, and in each of the nine sites there were three replicates, therefore, 28 litterbags were placed in each site, 84 per system with an overall of 252. All of these litterbags were used in the litter quality analysis in the following phase of this research.

At each collecting date, three series of litterbags containing the same material were collected from each of the TCS, RCS and Spmf parcels. The material remaining in the litterbags was oven dried for 48 hours at 60°C (Palm and Rowland, 1997). The mass loss was determined for all the samples. The single exponential model $W_t=W_0 e^{-kt}$ was used, where W_0 and W_t are the mass at the beginning of the experiment and after time t, respectively, and k is the rate decomposition constant.

The annual decomposition constant k was calculated according to the formula of Olson (1963):

$\ln(x_0/x_t) = -kt$ Where x_0 is the original mass of the litter, x_t is the mass remaining at time t, and t is the time in years.

For all experiments one way ANOVA followed by a Tukey test (Steel and Torrie, 1986) were used to analyze the data. Stepwise regressions were performed to determine correlations between mass loss and litter quality. The time required for 95% of the standing crop to decompose is estimated by 3/k, and for 99%, 5/k (Olson, 1963).

5.3 Results

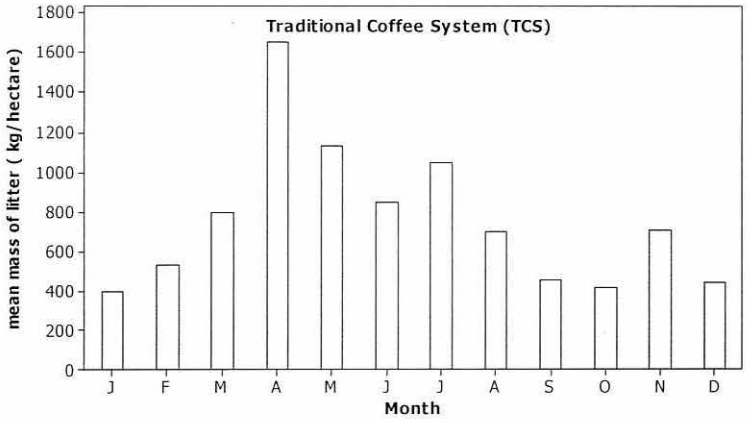
5.3.1 Leaf-litter production

The results of the total leaf litter production (Table 5.2) show that the TCS is the system that produced the most of leaf litter over the year with a total production of 9,121.45 ton/ha/year followed by the Spmf and RCS (8,190.03 and 5,752.66 ton/ha/year respectively). The presence of *Cecropia obtusifolia* contributed most to the total production during the year. The leaves of this species plus other such as *Dipholis minutiflora, Cordia alliodora, Malinkara sapota* and *Mastichodendron capirii* are large leaved and develop a waxy and thick cuticules and can resist decomposition, meanwhile other species such as *Inga* spp, have a faster rate of decomposition than the species already mentioned. These results are similar to the reported by Didhiam (1998) in continuos forest ranges from 6,196 and 7,948 kg/ha/yr, McDonald and Healey (2000) in Jamaica, were secondary forests were found to have a mean litter production of 9,319 kg/ha/yr and a review by Proctor et al. (1983) shows similar leaf litter production means in other tropical forests.

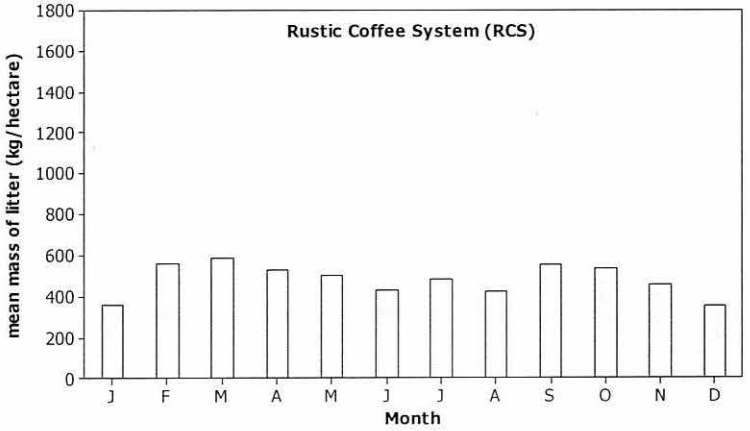
The highest production of leaf-litter in the three systems occurred during the months of February, March, April and May, which corresponds with the drought season and highest temperatures in the study region. The highest average litter production occurred during the month of April and May in TCS (1,650.60 and 1,132.80 kg/ha) which is coincident with the driest time of the year and the highest temperatures as well, followed by February in which was produced a mean total of 1,091.99 kg/ha in the Spmf. In the RCS the montly leaf litter production remained fairly constant over the year, with the lowest point during the winter months of December and January (Fig. 5.2).

As can be observed (Fig. 5.1 (a), (b) and (c)), a second production peak in the Spmf and TCS occurs at the end of the rainy season, in the month of November, which is coincident with the hurricane season in the Gulf of Mexico, to fall abruptly at the start of the drought season (January). These changes in litter production can be an effect of the species phenology and the climatic seasonality.

(a)



(b)



(c)

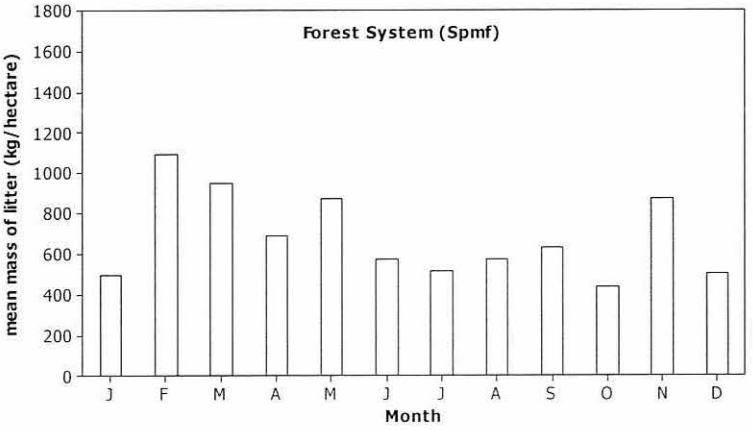


Figure 5.1 Monthly variations in the average mean mass of litter. (a):TCS, (b):RCS, (c):Spmf.

In the three systems, ten species were important in the leaflitter production, a comparison between systems and species is presented (Table 5.2). These species produce the highest average leaf-litter production during the year. The most productive species were *Cecropia obtusifolia* and *Heliocarpius appendiculatus* in TCS, *Robinsonella mirandae* and *Heliocarpus appendiculatus* in RCS and in Spmf were *Croton officinalis and Syderoxylon capiri* (Table 5.2). *Coffea arabica* has a small leaf litter contribution in the coffee systems similar to the shown by Beer (1988).

Taxonomic composition of litter

The percentages of taxonomic compositions of the litter collected in litter traps in three systems during the 12 months of the investigation are compared between in Table 5.2. The total mean mass of litter collected in the Traditional Coffee System (TCS) was 9,121.50 kg/ha/year, with *Cecropia obtusifolia* (27.6%), *Heliocarpus appendiculatus* (18.2%) and *Bauhinia divaricata* (14.1%) as the dominant species; for RCS the total mass of litter collected was 5,752.7 kg/ha/year, dominated by *Robinsonella mirandae* (14.3%), *Inga spp* (13.5%), *Heliocarpus appendiculatus* (11.3%), and other unidentified species (13.4%) and for Spmf the total mass of litter collected was 8,190.00 kg/ha/year, dominated by *Croton officinalis* (27.5%), *Syderoxylon capiri* (17.4%), *Piper hispidum* (1.9%), and *Robinsonella mirandae* (10.2%).

Table 5.2 Average leaf-litter production per dominant species (kg/ha/year^{-1})

Tree species	TCS	RCS	Spmf
Robinsonella mirandae	604.86	**772.14**	837.93
Coffea arabica	145.86	58.74	11.88
Mastichodendron capirii	385.7	3.8	63.08
Piper hispidum	47.19	299.91	976.56
Croton officinalis	20.16	584.64	**2,252.16**
Cecropia obtusifolia	**2,519.2**	451.2	582.8
Heliocarpus appendiculatus	**1,657.5**	**650.25**	441.15
Spondias mombin	N.a.	260.48	520.96
Syderoxylon capiri	176.88	344.38	**1,425.76**
Stemmaldenia donnel-smithii	8.32	588.8	336
Other species	3,555.78	1,738.33	741.75

Note: N.a. No available.

5.3.2 Leaf litter mass loss over time

The litter mass loss displayed characteristic decomposition patterns in that during the first phase of decomposition during the dry season (from January to May), *Robinsonella mirandae* in the three systems decomposed quickly during the first 176 days and continued almost linearly but at a slower rate of decomposition during the following 176 days and the percentage mass remaining was just 14 to 16 % (Fig. 5.3 (a)) and there were no differences in mass loss of *Robinsonella mirandae* between the three systems. During the dry season (176 d) the mass loss in *Robinsonella mirandae* averaged 65 % and during the rainy season (the next 176 d) 17 % more. There were no significant differences between systems and replicates.

Similar trends in decomposition rates were found in the litterbags containing *Robinsonella mirandae/Coffea arabica* and litter mix (Fig. 5.3 (b), and (c)), with a rapid loss of dry matter during the first 176 days and a slower decomposition rate for TCS (34.7 and 39.3%) and Spmf (43.3 and 33.3%) of dry mass. For the mass remaining in *Robinsonella mirandae/Coffea arabica* and litter mix in RCS, it follow the same trends during the first 176 days but showed the highest mass loss at 352 days, with a remaining mass of just 8.0 and 12.7 % respectively.

The litterbags containing *Robinsonella mirandae/Coffea arabica* leaf litter showed no differences in mass loss rates for the three systems ranging from 55 to 62 % of mass loss during the dry season, but in the rainy season, a higher mass loss was recorded for the RCS with 87 % of mass loss in comparison with TCS and Spmf with a 67 % of mass loss at the last date of sampling (352 d).

For the individual representative species (Fig. 5.3 (d)), *Mastichodendron capirii* in TCS show the slowest mass loss (44.7 % remaining mass) followed by *Croton officinalis* in Spmf (30.7) and *Piper hispidum* in RCS (0.7). The litter mix showed different mass loss patterns for the three systems following the order TCS > Spmf > RCS and mass losses of 60 %, 64% and 92% respectively. This can be due to the differences in species litter qualities of each system represented in the litterbags.

Litter mass loss for representative species per system followed different patterns. *Mastichodendron capirii* and *Croton officinalis* had a mass loss of approximately 55 % during the dry season with no further loss during the rainy season meanwhile *Piper hispidum* showed a mass loss of about 65% during the dry season and 100% by the end of the experiment. Probably, during the first 176 days, *Mastichodendron capirii* and *Croton officinalis* lost most of their water soluble compounds and nutrients.

For all the systems, the dry mass remaining varied by an order of magnitude: *Robinsonella mirandae* > *Robinsonella mirandae/Coffea arabica* > Mix > Representative species (*Piper hispidum* > *Croton officinalis* > *Mastichodendron capirii*). Initial relative weight loss varied significantly within species mixes and systems but not between replicates.

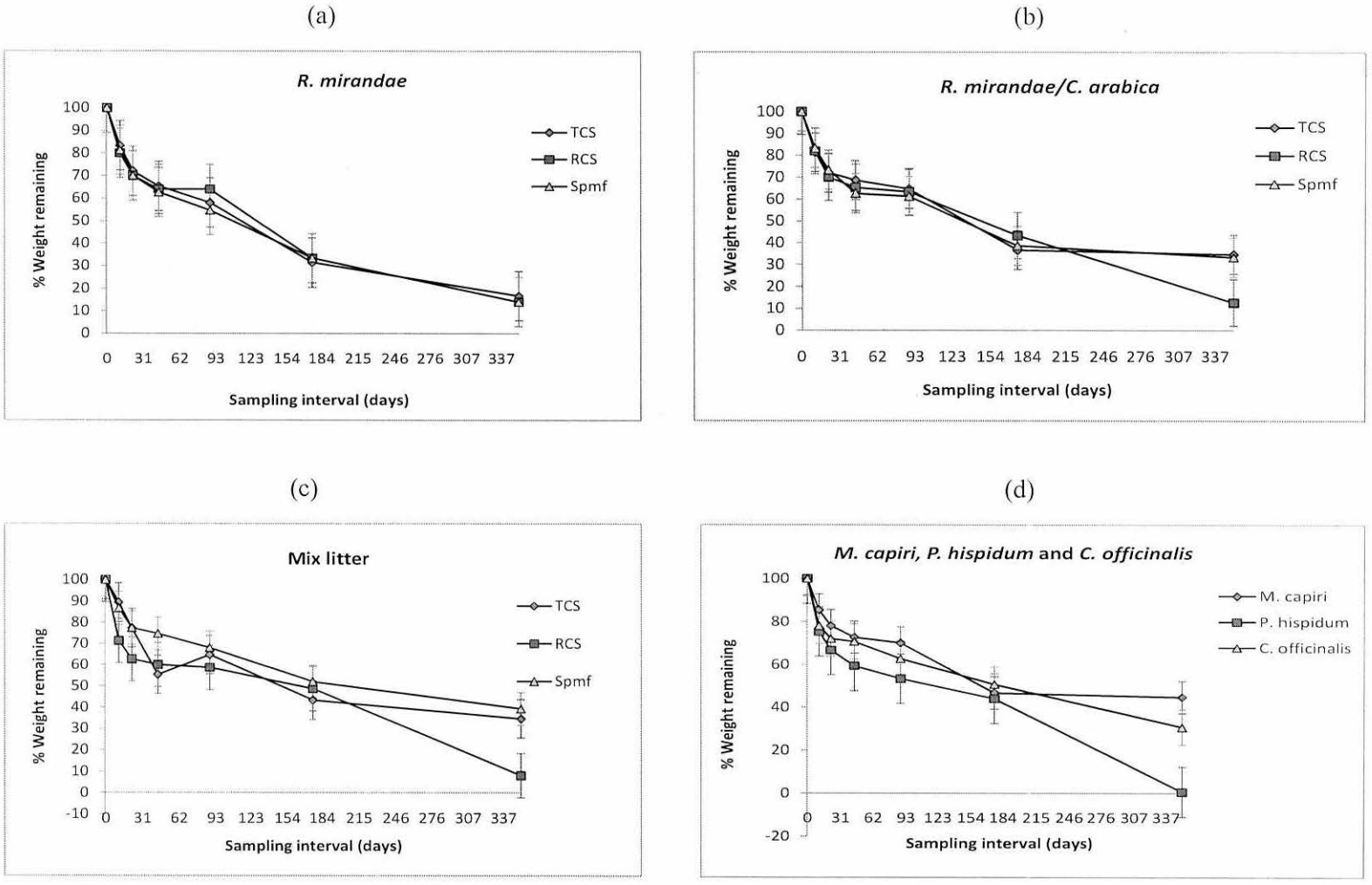


Fig. 5.2 Percentage of remaining weight in (a).- *Robinsonella mirandae*, (b).-*Robinsonella mirandae/Coffea arabica*, (c).-Mix litter and (d).- *Mastichodendron capirii, Piper hispidum and Croton officinalis* in TCS, RCS and Spmf in San Miguel, México.

5.3.3 Variations in the decomposition rate (k) of the leaf litter over time

Decay rate coefficients ("*k*") for all species ranged from -0.1278 (*Robinsonella mirandae/Coffea arabica* in Spmf) to 3.912 (*Piper hispidum*). Comparatively greater *k* values were observed between at the last 176 d of incubation in all the litter tested.

Estimated annual decay rates were slightly higher for *Robinsonella mirandae* (Fig. 5.4 (a)) than for *Robinsonella mirandae/Coffea arabica* (Fig. 5.4 (b)), the lowest values for rates of decay were obtained in Mix litter (Fig. 5.4 (c)) and *Mastichodendron capirii* and *Croton officinalis* (Fig. 5.4 (d)).

Robinsonella mirandae values ranged from 0.1.05 (11^{th} d) to 3.912 (352 d), and *Robinsonella mirandae/Coffea arabica* ranged from 0.1278 to 3.912 (11^{th} and 352 d respectively).

For RCS the lowest value was recorded at the beginning of the experiment but it remained low for most of the time, mix litter values ranged from 0.1508 (11^{th} d) (Fig. 5.4 (c)).

Mastichodendron capirii had the highest value at the beginning of the experiment (1.1054) and remained so during the dry season (first176 d) but at the beginning of the rainy season the decomposition rates lowed down to 1.0788. The highest rates were after 22 d of the experiment (Fig. 5.4 (d)).

Croton officinalis (Fig. 5.5), showed the lowest decomposition rate at the beginning of the experiment, and remained constant for most of the 352 d of the experiment. Medium rates of decomposition were obtained in *Piper hispidum* which recorde 0.3011 at the first 11 days but had the highest *k* values at the end of the experiment 3.912 (Fig. 5.4 (d) and 5.4 (d)), and the major dry weight loss as well.

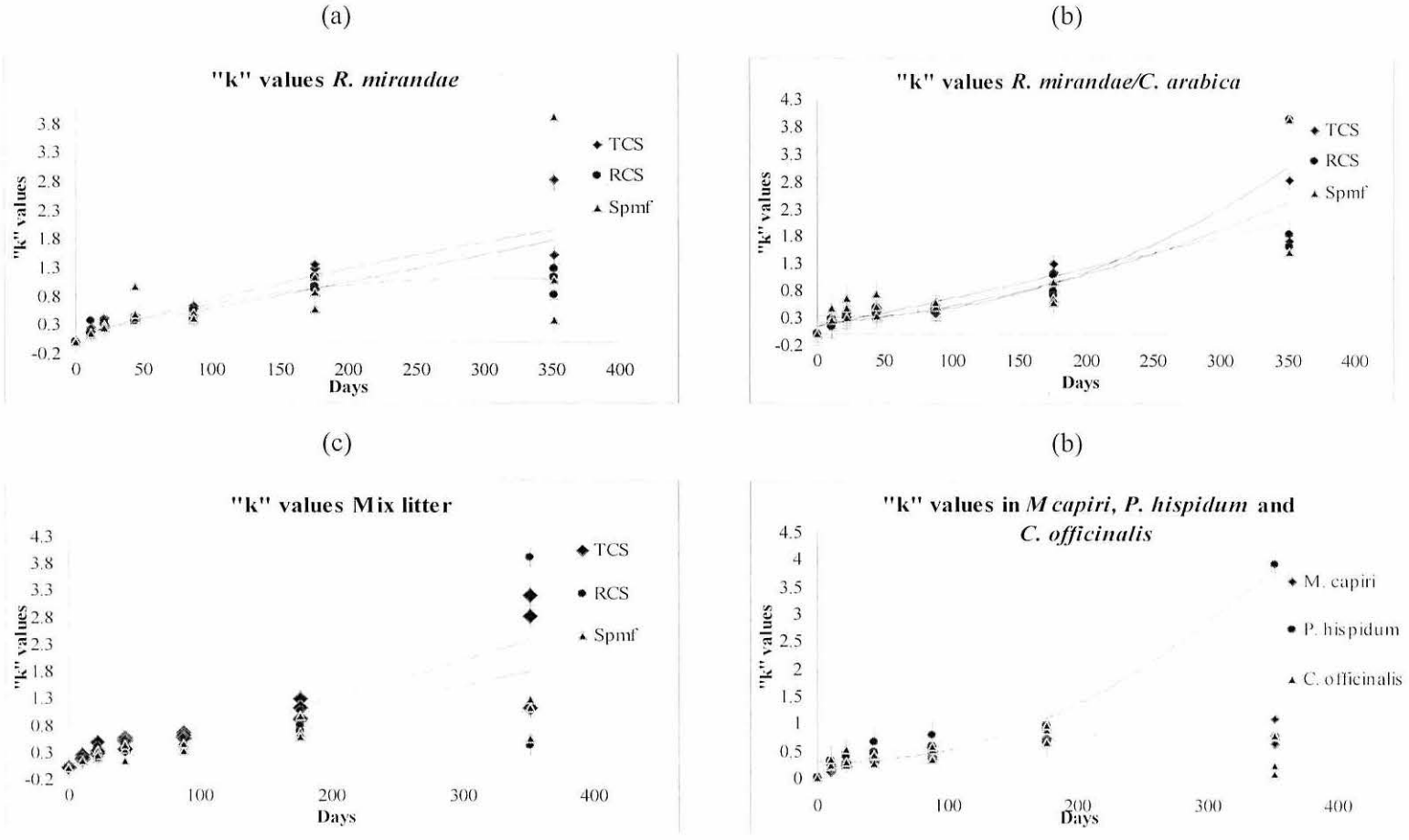


Fig. 5.3 Variations in the mean decomposition rates ("k" values) over time and system in (a).- *Robinsonella mirandae*, (b).-*Robinsonella mirandae/Coffea arabica*, (c).-Mix litter and (d).- *Mastichodendron capiri, Piper hispidum and Croton officinalis* in TCS, RCS and Spmf , in San Miguel, México.

The changes in the decomposition rate (k) of the leaf litters did not follow the same general trend in the systems (Figure 5.4). Most of the curves (for *Robinsonella mirandae* in TCS and Spmf, *Robinsonella mirandae/Coffea arabica* in TCS, RCS and Spmf, Mix litter in TCS and RCS, and *Piper hispidum*) showed a rapid increases followed by a decrease in decomposition rate over time. The curves for systems *Robinsonella mirandae* in RCS, Mix litter in Spmf and *Mastichodendron capirii* were asymptotic, providing evidence that no further increase in decomposition rate occurred after about 200 days. In the litter of *Croton officinalis* (low quality litter) the rate of decomposition initially increased, then declined rapidly after 200 days so that the curve was dome shaped.

The different shapes of the curves and the different values of the regression coefficients indicated different rates of change in the decomposition rates in the litter of each system. All of the polynomial regression equations were highly significant at $P \leq 0.01$ (Table 5.3).

ANOVA indicated that the decomposition rates of the leaf litters did not vary significantly within replicate samples, but did vary significantly between the litter/systems and between the times of sampling (Table 5.3). The interaction between time and litter type per system was significant. This implied that the changes in decomposition rate over time were not exactly the same in each system, but varied with respect to the different systems, as illustrated in Figures 5.3 and 5.4.

Table 5.3 Polynomial regression equations to describe variations in decomposition rate ("k") over time in *Robinsonella mirandae*, *Robinsonella mirandae/Coffea arabica, Representative mix litter per system* and *Mastichodendron capirii, Piper hispidum and Croton officinalis* in TCS, RCS and Spmf.

System/Litter	Equation	R^2 %	ANOVA(F)	P
1.- TCS *Robinsonella mirandae*	D= 0.0892 + 0.006741 Time - 0.000004 $Time^2$	85.8	54.37	0.000***
2.- TCS *Robinsonella mirandae /Coffea arabica*	D= 0.1301 + 0.005143 Time + 0.000001 $Time^2$	89.3	74.98	0.000***
3.- TCS Mix litter	D= 0.1427 + 0.005200 Time + 0.000003 $Time^2$	81.3	39.23	0.000***
4.- RCS *Robinsonella mirandae*	D= 0.0847 + 0.006749 Time + 0.000011 $Time^2$	89.1	73.47	0.000***
5.- RCS *Robinsonella mirandae /Coffea arabica*	D= 0.1804 + 0.002131 Time + 0.000012 $Time^2$	77.2	30.49	0.000***
6.- RCS Mix litter	D= 0.1448 + 0.004010 Time + 0.000002 $Time^2$	47.6	8.18	0.003**
7.- Spmf *Robinsonella mirandae*	D= 0.1292 + 0.004397 Time + 0.000001 $Time^2$	45.1	7.40	0.005**
8.- Spmf *Robinsonella mirandae /Coffea arabica*	D= 0.3218 + 0.000871 Time + 0.000025 $Time^2$	79.7	35.41	0.000***
9.- Spmf Mix litter	D= 0.0759 + 0.004753 Time - 0.000006 $Time^2$	80.7	37.57	0.000***
10.- TCS *Mastichodendron capirii*	D= 0.1698 + 0.005242 Time - 0.000009 $Time^2$	88.1	66.79	0.000***
11.- RCS *Piper hispidum*	D= 0.2994 + 0.001138 Time + 0.000032 $Time^2$	97.3	323.12	0.000***
12.- Spmf *Croton officinalis*	D= 0.0975 + 0.006956 Time - 0.000018 $Time^2$	65.2	16.87	0.000***

Note: TCS: traditional coffee system; RCS: rustic coffee system and Spmf: subperennial médium forest. D= Decomposition

5.4. Discussion and conclusions

Leaf litter mass loss over time

There are many drivers of decomposition that include the effect of the environment (macro and micro climate) the quality of the substrate and composition of the decomposer community (Swift et al., 1979; Aerts, 1997; Aerts and De caluwe, 1994; Parton et al., 2007). These influence losses due to catabolism, removal or export following comminution, and leaching. Mean percentage dry weight loss was determined for each of the mixes tested in the litterbags over the incubation time "in situ". An initial faster rate of disappearance was followed by a subsequent slower rate, in agreement with the results reported for litter decomposition by Anderson and Swift (1983); Swift and Anderson (1989); Jama and Nair (1996), and others.

Decomposition process may apparently be divided into two phases controlled by different factors. An initial phase with a faster rate of disappearance of mass litter followed by a subsequent slower rate is in agreement with the results reported by others (Anderson and Swift, 1983; Swift and Anderson, 1989; Sundarapandian and Swamy, 1999; Loranger et al 2002; Xuluc-Tolosa et al., 2003).

During the collect of the litterbags samples over the 352 d, different types of micro-organisms, micro-fauna and fungus of different types were observed. Differences in loss mass between sites (RCS vs TCS and Spmf) may be caused by either environmental factors or variation in substrate concentrations (Sundarapandiam and Swamy 1999), earlier decomposition rates are strongly related to climate and litter concentrations of water soluble compounds (Berg, 2000), while later decomposition rates are more influenced by lignin content of litter because they can slow the decomposition and affect the surrounding soil and litter (Melillo et al, 1982; Couteaux et al, 1995; Chadwick et al., 1998, 2001; Preston and Trofymow, 2000).

The first stage of decomposition, the mass loss may have been influenced as result of the high content of water soluble and simple components and the breakdown of the litter by decomposers, specially the micro-organisms and small insects. The relative slower decay during the second phase of decomposition (176 to 352 days) may be due

to the accumulation of resistant components such as the lignin and phenols which subsequently slow the decomposition rate of the resource and are no longer a source of energy for most decomposer organisms.

The higher relative mass loss during the rainy season for *Piper hispidum* and the litterbags in the RCS compared to the dry season might be due to physical determinants in the site such as soil moisture content, temperature and their effect on the micro-organisms decomposers activity (Facelli and Pickett 1991). Decay rates coefficients ("k") in the present study were high for all the litter tested in the RCS and *Croton officinalis* for all the sampling dates, probably indicating an effect of the microclimate or the mixture of litters on the rates of decomposition. The lowest decomposition rates were shown in Mix litter on TCS, Spmf and *Mastichodendron capirii* while the rest of the litter showed medium rates of decomposition.

Decomposition increased with the onset of the dry season, from January to end of May (the first 176 d.) and then stayed low and relatively constant for the latter part of the experiment (176-352 d). However, *Piper hispidum*, Mix litter and *Robinsonella mirandae/Coffea arabica* in RCS started losing mass first, followed by *Robinsonella mirandae* in the three systems. *Piper hispidum* showed the greatest mass loss by the end of the experiment.

The fact that decomposition did not vary among sites at least for *Robinsonella mirandae* (for the three systems), *Robinsonella mirandae/Coffea arabica* and Mix litter (TCS and Spmf) seems to indicate that moisture and temperature are not the overriding determinants for litter decay. Perhaps differences in the litter chemical composition in some cases as a result of the mix of the tree species in each of the systems tested could influence it

It is evident that periodicity of litterfall is largely influenced by annual climatic variations particularly the dry and the wet season (Jackson, 1978; Proctor, 1983; Proctor et al., 1983; Beer, 1988; Dantas and Phillipson, 1989; Scott and Binkley, 1997; Kumar and Deepu, 1992; Liu et al., 2003b) and decomposition dynamics (Beer, 1988; Liu et al., 2003a). However, the results of this study seem to indicate that litterfall peaks do have relation with the rainfall variation and the phenology of the

tree canopy composition. This emphasizes the need for long-term litterfall studies to confirm seasonal periodicity and establish relations between rainfall and litterfall peaks.

Chapter 6 Leaf litter quality influence on decomposition rates in TCS, RCS and Spmf in San Miguel, Veracruz. México.

6.1 Introduction

6.1.1 Litter quality and the decomposition process

Studies of litter quality and changes over time have been widely documented over the last decades and the results obtained have been diverse over different locations and biomes (Cornwell et al., 2008; Zhou et al., 2008a), climates (Fonte and Showalter, 2004), decomposer communities (Wardle and Lavelle, 1997) vegetation types (Swift et al., 1979; Wood et al., 2005 and 2006; Zhou et al., 2008b) and greenfall vs senescent foliage (Fonte and Schowalter, 2004). The concentrations of nutrients in the litter material are determinant for the quality of the material and have a direct influence on the rates of decomposition (Swift et al., 1979).

Besides the soil conditions, chemical quality of the litter, and climate the main cause of variation in chemical composition of plant tissues is through selection of plant species (Heal et al., 1997) and their major life form (annual, deciduous or evergreen perennial etc).

The nutrients taken up by the roots and translocated through the plant accumulate in different concentrations in the plant organs. The distribution of nutrients is determinated by the relative activity of the plant tissues, the most productive, store the most nutrients. In this respect, the photosynthetic tissues in the leaves always have the highest nutrient concentrations followed by the young roots and twigs. The perennial tissues such as the bark and branches have the lowest nutrient concentrations in all the plant (Swift et al., 1979). The main components of litter fall by dry weight are the leaves and their production is of vital importance in ecosystems with limited access to nutrient sources as in some tropical ecosystems.

The term "litterfall quality" mainly refers to the content of nutrients and comparative decomposition speed of the vegetal remainders (Anderson and Swift, 1983). The type of litterfall that is considered of high quality is that which has a high nutrient content

particularly nitrogen and that is not recalcitrant, whereas the ligneous remainders and other lignified materials like the straw of some cereals are more resistant to decomposition and therefore of a lower quality. Nevertheless, there exists an interspecific variation in the quality and amount of litterfall produced by different species, which is the reason why decomposition (and therefore, the cycle of C and N) is determined by the characteristics of the dominant species that compose the system.

These litterfall decomposition rates are regulated by a series of hierarchical bio-physical factors (Sariyildiz and Anderson, 2003) with fungi and bacteria as decomposition agents. Different resource types consistently decompose at different rates even under controlled conditions.

Heal et al. (1997), recognizes three different chemical attributes of the leaf litter material: carbon and the energy sources; nutrients in the leaf litter and finally, molecules which can inhibit or stimulate the growth of decomposer colonies of micro-organisms. These molecules are often (not always) very active but at relatively lower concentrations.

6.1.2 Chemical quality parameters of leaf-litter

Decomposition and nutrient release patterns of organic matter are determined by the organic constituents and the nutrient content of the organic matter, the decomposer colonies and the environmental conditions. According to Palm and Rowland (1997), some of the quality parameters that can be important to measure litter quality depending on the decomposition stage are for initial stages: The litter can play at least two principal roles in the ecosystems: it can be the main source of nutrients that will form part of the nutrient cycle of the forest (Montagnini et al., 1993) and secondly, it can be a determining factor to protect the forest floor from climatic and physical conditions erosion and soil compaction (Geddes and Dunkerley, 1999, Wilcox et al., 2003), and to form and conserve micro-climatic conditions important for the development of microorganisms in the soil, nitrogen, polyphenols, and for later stages in S.O.M. and decomposition: carbon and lignin (Swift et al., 1979; Wardle and Lavelle, 1997; Janzen, 2004).

The N and P concentration, C: N ratio, Lignin, Lignin: N ratio and polyphenols can play important roles in governing the rates of decomposition and in N mineralization. The N content was the first litter chemistry parameters used to predict decomposition rates but C:N ratio showed to be a good parameter in some studies (Swift et al., 1979; Tian et al., 1997), this ratio has been found to be of critical importance (Bocock, 1964; Jenny, 1994; Zhang et al., 2008; Zhou et al., 2008a). Other studies in tropical ecosystems have found that the P and C:P ratio (Vitousek, 1984; Vitousek et al., 1994; Güsewell and Gessner, 2009), can influence the rates of decomposition.

Litterfall quality studies indicate other factors able to predict the decomposition rates in litter-fall rather than the C:N ratio and lignin:N. One of these factors is the content of polyphenolics and lignin (Giller, 2000; Schroth and Sinclair, 2003), since both compounds in high quantities can slow down the decomposition of the vegetal material (Palm, 1995) and therefore can be considered as low quality. Organic materials with a low C:N ratio (<25) and low concentrations of lignin (<15%) and polyphenolics (<3%) are considered to be high quality because of the fast release of the nutrients and high rates of decomposition (Palm and Sanchez, 1990).

Litterfall decomposes faster in tropical than in temperate ecosystems. For example in boreal and tundra zones, the physical conditions as well as low temperatures and low quality nutrient availability and the negligible soil animal component limit the decomposition rates. In contrast, in tropical zones there are better physical conditions of temperature and humidity, a higher quality (but variable) and an active and major fauna component (Swift et al, 1979). In the Amazonian forests, litterfall is decomposed more slowly than in other forests that grow over more fertile soils (Medina and Cuevas, 1996) because of the low Lignin:N proportion (Cuevas and Medina, 1988). Litter with low quality can make an important contribution in conserving the soil than more rapidly decomposing litter (Hairiah et al., 2006), and helps to create better microclimatic conditions in which the decomposer micro-organisms grow.

The objective in this chapter was to investigate the changes of the leaf litter quality in four litter types, representing the most representative litter species in TCS, RCS and Spmf. The objectives were: (1) to evaluate the relative importance of the leaf litter

quality and their changes over time, and (2) to estimate the influence of different parameters measured during 352 days in these systems.

The hypotheses were:

a) There are differences in initial quality of the leaf litter produced in each of the study systems, characterized by their N, lignin, cellulose, hemicelluloses concentrations and C:N and Lignin:N ratios.

b) The best quality parameters to explain the variability in the decomposition over time are N, P, C:N and Lignin:N ratios.

6.2 Materials and Methods (see Chapter 4)

6.2.1 Chemical analysis of leaf litter

The contents of the litterbags used during the loss of mass experiment were utilized to perform chemical analyses to establish the degree and changes in the quality of the leaf litter tested. After the collection of the litterbags during the sampling dates, the leaf litter material was dried; the leaves were chopped and mixed, in order to obtain homogeneous samples for the subsequent laboratory analysis. After obtaining a homogeneous sample, foliage was ground to a fine dust in a cutting mill for subsequent nutrient analyses. The fitness of grinding is an important consideration, because is governed by the weight of sample required for the analysis which should be representative of the whole material, and is recommended for this purposes that the biological material, should pass a mesh of a size of 0.5 mm, which is the smallest mesh provided with most grinders, but in practice, most of the material is broken in smaller size particles. The dried samples were stored in well-sealed containers in a dry warm room to avoid any attack by fungi and bacteria to the material to reduce any uptake of humidity.

6.2.2 Nutrient contents analysis

The laboratory nutrient analyses for N, P, K, Ca and C for each of the litter bags material collected from the field were performed, using the methodology of Grimshaw et al. (1989), the hemicelluloses, cellulose and lignin were analyzed using

the ANKOM technology method (ANKOM, 2008 a, b, and c) and C (CE instruments NC2100, Thermo Quest, Italy). The following methods were used for the determination of the leaf litter parameters (Table 6.1):

Table 6.1 Methods for determination of quality litter parameters.

Chemical parameter	Method of determination
Nitrogen (*):	Diacid mixture digestion procedure (Kjeldahl digestion);
Phosphorus (*):	Vanado-molybdate method (Kitson and Mellon, 1944);
Potassium (*):	Spectrometry Flame emission (FES) method;
Calcium (*):	Atomic absorption spectroscopy (AAS);
Carbon (**):	Dry combustion techniques (CE instruments NC 2100, Thermo Quest, Italia);
Hemicelluloses + Cellulose + Lignin (***):	Neutral detergent fibre, Filter bag technique (ANKOM (2008 b))
Cellulose + Lignin (***):	Acid detergent fibre, Filter bag technique (ANKOM (2008 a))
Lignin (***):	Acid detergent lignin in beakers (ANKOM (2008 c))

Note: *N, P, K, Ca analysis were performed in Departamento de Suelos, Laboratorio Central, Universidad Autónoma de Chapingo, México. **C analysis at Dept of Biology, Duke University (Durham, USA); and ***Hemicelluloses, Cellulose and Lignin analyses were performed in an ANKOM^{2000} at Bangor University (SENR), U.K. All analyses were performed in duplicate.

Carbon and nitrogen concentrations (for C:N ratios) were determined by the dry combustion method using a NC 2100 Soil (ThermoQuest CE Instruments, Milan, Italy). Leaf litter subsamples were ground using a ball mill. Size fractions were ground using a mortar and pestle and passed through 250 μm sieve, 4–5 mg of grounded leaf litter were accurately weighed and placed in tin capsules (8-5 mm) and combusted at 1200 °C in an elemental analyzer in the presence of chemical catalysts to produce CO_2 and N_2.

6.2.3 Neutral detergent fibre (NDF) and Acid detergent fibre (ADF)

Neutral Detergent Fibre is the residue remaining in a detergent solution which is composed predominantly of hemicelluloses, celluloses and lignin. Filter bags with 0.455 to 0.5 g of prepared leaf litter samples were weighed and sealed before being placed in an ANKOM Fibre Analyzer, with a maximum of 24 bags running. Water was heated to 70°C and at the start of the process 20g of Na_2SO_3 and 4 ml of alpha-amylase were added manually. During the two following rinses, two more additions of alpha-amylase diluted in 350 ml of distilled water were done. When the fibre analyzer process was finished, the filter bags excess of water was removed manually.

The bags then were placed in a 250 ml beaker with enough acetone to cover the bags and soaked for 5 min. The excess of acetone in the bags was evaporated by air-drying. Filter bags were then over-dried at 80°C for 12 hours. The bags were cooled to ambient temperature and weight. Calculations for %NDF were made using the following formula:

$$\%NDF = \frac{(W3 - (W1xC1))}{W2} x100$$

Were:

W_1=Bag tare weight

W_2=Sample weight

W_3=Dried weight of bag with fibre after extraction process

C_1=Blank bag correction (Final oven dried weight divided by the original blank bag weight).

The acid detergent fibre is the residue after digesting with H_2SO_4 and Cetyl-trimethylammonium bromide (CTAB); the residues are predominantly celluloses and lignin. The methodology is the same as for NDF with the difference that an acid detergent solution is used (20 g CTAB to 1 l 1N H_2SO_4 previously standardized.
After the completion of the fibre analysis and once the bags are dried, calculations were done as for % NDF.

6.2.4 Acid detergent lignin (ADL)

After the determination of ADF, the dried bags were placed in beakers and covered with approximately 250 ml of 72% H_2SO_4 and agitated every 30 minutes for 3 hours. The H_2SO_4 was then poured off and the bags were rinsed with tap water to remove all the acid. This was done until the pH was neutral, and then the bags were rinsed in approximately 250 ml of acetone for 3 minutes to remove excess water and then dried in an oven at 80°C for 24 hours, the residue is predominantly lignin.. When dry, the bags were weighed and then ashed at 525°C for 3 hours. The samples were cooled to ambient temperature and the weight loss calculated (W_4). A blank bag was burned in order to obtain the bag ash correction using a weight loss upon ignition.

The % ADL was calculated using the formula:

$$ADL(OM) - DM\ basis = \frac{(W4 - (W1xC2))}{W2xDM} x100$$

Were:

W_1=Bag tare weight;

W_2= Sample weight;

W_3= Weight after extraction process;

W_4= Weight of organic matter (OM) (loss of weight in ignition of bag and fibre residue);

C_1= Blank bag correction (final oven-dried weight / original blank weight);

C_2= Ash corrected blank bag (loss of weight on ignition of bag / original blank bag).

6.2.5 Statistical analysis

Leaf litter quality parameters and quality changes over time data were analyzed using analysis of variance (ANOVA) with a Tukey's studentized range test ($\alpha = 0.05$, SPSS program version 12, Pallant, 2004). Stepwise regressions were performed to determine correlations between time and litter quality parameters.

6.3 Results

The aim of the statistical analysis was to determine if the chemical contents and decomposition rates of each of the leaf litter types (3 replicates per bag) varied significantly with respect to two experimental factors, namely (i) the time of incubation and (ii) the systems (TCS, RCS and Spmf). The time of incubation corresponded to 7 sampling intervals of 0, 11, 22, 33, 88, 176, and 352 days.

The system factor was coded as defined in Table 6.2 (a), where TCS = traditional coffee system, RCS= rustic coffee system and Spmf = forest system. The response variables were the quality parameters constituents of the leaf litter i.e. N (nitrogen), P (phosphorus), K (potassium), Ca (calcium), lignin, cellulose, hemicelluloses.

Table 6.2 (a). Initial quality (mean ±SD) of the leaf litter in TCS, RCS and Spmf

System type	Leaf litter type	Initial Lignin:N ratio	Initial C:N ratio	Leaf litter Quality
1.-TCS	*Robinsonella mirandae*	37.51±0.003	24.59±0.005	medium
2.-TCS	*R. mirandae/C. arabica*	35.14±0.006	22.03±0.003	medium
3.-TCS	*Mixed*	35.34± 0.008	23.12±0.002	medium
4.-RCS	*Robinsonella mirandae*	32.98±0.006	25.51±0.001	medium
5.-RCS	*R. mirandae/C. arabica*	34.74±0.004	21.14±0.005	medium
6.-RCS	*Mixed*	28.67±0.013	21.15±0.005	medium
7.-Spmf	*Robinsonella mirandae*	27.75±0.002	25.51±0.001	medium
8.-Spmf	*R. mirandae/C. arabica*	19.25±0.001*	21.29±0.002	high
9.-Spmf	*Mixed*	28.14±0.005	20.39±0.005	medium
10.-TCS	*Mastichodendron capirii*	47.09±0.024*	25.93±0.005	high
11.-RCS	*Piper hispidum*	40.82±0.002*	19.35±0.012	high
12.-Spmf	*Croton officinalis*	21.26±0.005*	21.08±0.012*	low
ANOVA (F)		6.38	8.92	
P		0.000***	0.000**	

Note: *R. mirandae=Robinsonella mirandae:,C. arabica=Coffea arabica*

One-Way Analysis of Variance (ANOVA) indicated a highly significant difference between the initial mean Lignin:N and C:N ratios of the leaf litters in the three systems. Tukey's HSD test indicated that the ratios in *Robinsonella mirandae/Coffea arabica* (Spmf), *Mastichodendron capirii, Piper hispidum* and *Croton officinalis* were significantly different to the others. On the basis the differences between their Lignin:N and C:N ratios, the leaf litters were classified as "low" "medium" and "high" qualities (Table 6.2 (a)).

One-Way ANOVA indicated that the mean initial N, P, K, Ca, lignin, cellulose, and hemicelluloses contents of the leaf litters varied very significantly between the litter types and systems (Table 6.2 (b)). *Robinsonella mirandae/Coffea arabica* (RCS), and the representative species *Mastichodendron capirii, Piper hispidum* and *Croton officinalis* stood out as different to the others.

Table 6.2 (b) Initial chemical compositions (dry weight basis) of leaf litter from *Robinsonella mirandae, Robinsonella mirandae/Coffea arabica*, Mix litter, *Mastichodendron capirii, Piper hispidum* and *Croton officinalis* in TCS, RCS and Spmf.

System/Litter	N %	P %	K %	Ca%	Lignin (Beakers%)	Cellulose (ADF%)	Hemicellulose (NDF%)	Other %
1.- *Robinsonella mirandae*	1.52±0.08	0.15±0.02	0.30±0.03	6.00±0.99	21.22±0.003	17.18±0.004	13.49±0.02	40.14±0.02
1.- *R. mirandae/C. arabica*	1.59±0.04	0.14±0.01	0.33±0.05	6.74±1.40	22.23±0.01	20.33±0.004	10.49±0.01	38.15±0.01
1.- Mix litter	1.46±0.02	0.13±0.003	0.34±0.05	6.37±0.42	25.57±0.01	18.59±0.004	9.13±0.04	38.41±0.01
2.- *Robinsonella mirandae*	1.80±0.04	0.14±0.003	0.58±0.10	4.54±0.86	20.89±0.01	25.89±0.001	9.84±0.01	36.32±0.01
2.- *R. mirandae/C. arabica*	1.80±0.28	0.12±0.02	0.67±0.33	5.23±0.79	25.06±0.01	28.06±0.004	4.42±0.01	34.64±0.01
2.- Mix litter	1.80±0.24	0.13±0.02	0.53±0.14	5.66±0.53	25.66±0.01	21.80±0.003	6.54±0.03	37.88±0.02
3.- *Robinsonella mirandae*	2.16±0.06*	0.09±0.02*	0.56±0.02	3.15±0.30	25.43±0.004	23.04±0.001	8.49±0.01*	37.08±0.02
3.- *R. mirandae/C. arabica*	2.01±0.08*	0.11±0.01*	2.04±0.25*	2.14±0.62*	13.58±0.002	19.59±0.001	10.58±0.01	49.95±0.02
3.- Mix litter	2.03±0.06*	0.12±0.01	2.02±0.17*	5.69±2.23	28.20±0.007	24.11±0.009	7.22±0.01	30.61±0.01
1. Mastichodendron capirii	1.56±0.34	0.08±0.02*	0.49±0.16	3.57±0.60	24.68±0.03*	21.66±0.004*	7.81±0.01	40.15±0.03
2. Piper hispidum	1.80±0.12	0.08±0.03*	2.06±0.52*	4.68±0.81	16.85±0.001*	23.23±0.001*	17.99±0.01	33.31±0.01
3. Croton officinalis	1.35±0.03*	0.06±0.004*	1.11±0.35*	2.50±0.50*	24.69±0.006*	29.05±0.015*	4.36±0.01*	36.88±0.01
ANOVA F	7.75	8.36	27.78	6.51	5.72	9.03	3.25	5.15
P	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.008**	

Note: 1=TCS; 2= RCS; 3=Spmf. Values are means ± SD (n=21). *R. mirandae/C. arabica= Robinsonella mirandae/Coffea arabica*
Hemicelluloses=Hemicelluloses+Celluloses+lignin, Cellulose= Cellulose+lignin. Other= Wax, other nutrients, ashes.

Tukey's pair-wise comparison tests indicated that the litter samples in *Croton officinalis* (classified as low quality) had significantly lower initial mean N, P, Ca and hemicelluloses, but significantly higher initial mean K, Lignin and cellulose than the other litters. The litter samples in *Mastichodendron capirii* and *Piper hispidum* (classified as high quality) had significantly lower initial mean P, lignin, and cellulose than the low quality litter. *Robinsonella mirandae/Coffea arabica* in RCS (classified as high quality) had significantly higher initial mean N and K but lower initial mean Ca than the low quality litter.

Following the description of initial conditions (Tables 6.2 (a) and (b)) subsequent changes in the chemical contents and decomposition rates of the leaf litter samples over time in each of the litter types per system were described by means of regression equations. Simple linear regression was not considered appropriate since changes in the chemical content and decomposition of leaf litter are not necessarily linear with respect to time. Polynomial regression equations of the form $Y = \beta_0 + \beta_1 X + \beta_2 X^2$ were therefore constructed, where Y = dependent variable; β_0 = intercept (value of Y when X = 0), β_1 and β_2 = regression (slope) coefficients; X = dependent variable (time in days) were considered appropiate.

The statistical significance of each regression equation was indicated using the value of R^2 (coefficient of determination, which indicates the percentage of the variance in the dependent variable explained by the independent variable) the F (variance ratio) and the P (probability) value obtained by Analysis of Variance. Although it was appreciated that the data may violate the assumptions of regression (particularly that of homogeneity of variance) the polynomial regression equations served to describe different patterns and trends in the chemical contents and decomposition rates of the leaf litters with respect to time.

Two-way Analysis of Variance (ANOVA) was applied to determine the effects of the two experimental factors (sampling time and litter/system) on the quality of the litter and the decomposition rates of the leaf litter samples. The null hypotheses were the two factors had no effect on the mean chemical contents or the mean decomposition rates of the samples, and that there were no significant interactions between the effects of time and litter type per system. Interaction implies that the effects of one factor depend on the levels of another factor. If interaction is significant, the variables does not respond in exactly the same way to each of factor. If interaction is not significant, then the effects of the factors are additive i.e. the variables respond in exactly the same way to the each of the factors.

A repeated measures analysis of variance (von Ende, 1993; Xuluc-Tolosa et al., 2003) was applicable because the data violated the assumption of independence, i.e. all the measurements were not collected from completely separate sampling sites at the same time. Measurements were repeated on seven occasions over a period of 352 days at the same sampling sites. Consequently, the samples from each site were not independent, so that the values of the variables in previous samples may have influenced the values in subsequent samples. Standard ANOVA is inappropriate for this kind of data, because the correlations

between the repeated measures are not modeled. The random effect of the "within samples" variance (the inherent variability within a group of replicates collected at one time) which might otherwise influence the results was also taken into account. If a standard ANOVA was performed, without taking random differences between the contents of the replicate litter bags into account, this could have added another source of variability which confounded the variance of the response variables, and could make it difficult to determine if there were any significant differences "between systems" and "between times".

Whilst ANOVA is relatively robust with respect to violation of assumptions, it was expected that some of the results may have been influenced by non-homogeneity of variance. Levene's test was therefore applied to check this assumption. Levene's test considers the distances of the observations from their sample median rather than their sample mean, making it more robust for smaller sample sizes which are not necessarily normally distributed.

The convention used to assess the significance of the statistics was ^{ns} not significant ($P > 0.1$); ^{ms} marginally significant ($P \leq 0.1$); * significant ($P \leq 0.05$); ** very significant ($P \leq 0.01$); *** very highly significant ($P < 0.001$).

The results of the statistical analyses were used to test research hypotheses based on previous investigations on leaf litter decomposition (Swift et al, 1979; Aber et al., 1990; Lavelle et al., 1993; Aerts, 1997; Aber and Melillo, 2001; Baker et al., 2001) in particular that (a) high quality litters (e.g. with lower Lignin:N ratios) are expected to decompose faster than low quality litters (with higher Lignin:N ratios) and (b) patterns of variation in the chemical constituents of leaf litters with respect to time and litter/system (coffee and native forest systems) will be related to the quality and taxonomic composition of the litters.

6.3.1 Variations in the nitrogen content of the leaf litter over to time

The changes in the N content of the leaf litter over time followed the same general patterns and trends in the leaf-litter analysed (Figure 6.1 (a), (b), (c) and (d)). All of the curves were dome shaped, reflecting an initial accumulation phase of N, followed by a decline phase. All but one of the polynomial regression equations (for *Robinsonella mirandae/Coffea arabica* in RCS) was significant at $P < 0.1$ (Table 6.3.). The equation for *Robinsonella mirandae/Coffea arabica* in RCS was not significant due to the very high variance in N content on day 352, illustrated by the wide divergence of points in Figure 6.1 (b).

Table 6.3 Polynomial regression equations to describe variations in nitrogen over time in *Robinsonella mirandae* (a), *Robinsonella mirandae/Coffea arabica* (b), Mix litter (c) and *Mastichodendron capirii, Piper hispidum* and *Croton officinalis* in TCS, RCS and Spmf

System	Regression equation	R^2	ANOVA(F)	P
TCS (a)	N = 1.419 + 0.01448 - 0.000052	83.3	7.67	0.012*
RCS (a)	N = 1.486 + 0.009222 - 0.000017	66.3	17.67	0.000***
Spmf (a)	N = 1.695 + 0.01306 - 0.000037	27.5	3.41	0.056^{ms}
TCS (b)	N = 1.462 + 0.007042 - 0.000023	18.8	0.71	0.154ns
RCS (b)	N = 1.489 + 0.008623 - 0.000013	72.9	24.17	0.000***
Spmf (b)	N = 1.642 + 0.01207 - 0.000047	88.8	71.70	0.000***
TCS (c)	N = 1.365 + 0.01243 - 0.000038	34.1	4.65	0.024*
RCS (c)	N = 1.433 + 0.01133 - 0.000028	26.2	3.19	0.065ms
Spmf (c)	N = 1.598 + 0.003158 - 0.000003	34.4	4.19	0.034ns
Mastichodendron capirii	N = 1.460 + 0.02150 - 0.000064	58.8	12.86	0.000***
Piper hispidum	N = 1.651 + 0.006275 - 0.000030	59.9	13.47	0.000***
Croton officinalis	N = 1.328 + 0.008744 - 0.000018	74.7	26.52	0.000***

ANOVA indicated that the N content of the leaf litter did not vary significantly within replicate samples, but did vary significantly between the Litter types/systems and between the times of sampling (Annex 6.1). The interaction between time and system was significant. This implied that the changes in N content over time were not exactly the same in each system, but varied with respect to the different systems, as illustrated in Figure 6.1 ((a), (b), (c) and (d)). *Robinsonella mirandae, Robinsonella mirandae/Coffea arabica* litter in TCS, Mix litter in RCS and Spmf and *Piper hispidum* and *Croton officinalis* were characterized by low and medium overall mean N contents < 2.0 whereas those in *Robinsonella mirandae* (RCS and Spmf), *Robinsonella mirandae/Coffea arabica* (RCS) and *Mastichodendron capirii* were characterized by high overall mean N contents > 2.0.

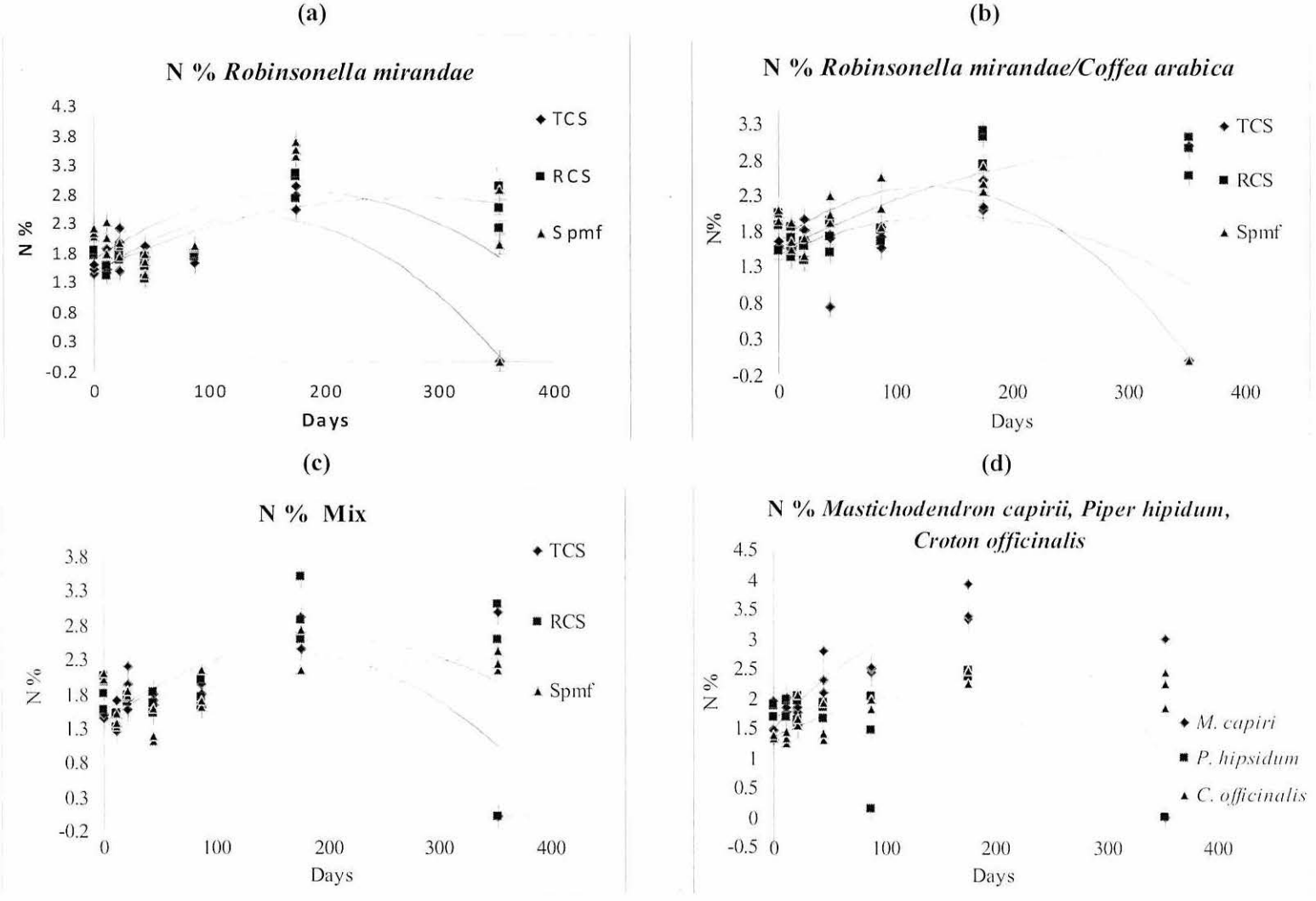


Figure 6.1 Regressions of N content of leaf litter over time in *(a).- Robinsonella mirandae; (b). - Robinsonella mirandae/Coffea arabica; (c).-Mix litter* and *(d).-Mastichodendron capirii, Piper hispidum and Croton officinalis* in TCS, RCS & Spmf.

6.3.2. Variations in the phosphorus content of the leaf litter over time

The changes in the P content of the leaf litter over time followed the same general pattern in most of the litter/systems (Figure 6.2 (a), (b), (c) and (d)), at those for the N content. All but one of the curves (for Mixed litter in Spmf) in Figure 6.2 (c) were dome shaped, reflecting an initial accumulation phase of P, followed by a decline. All but three of the regression equations (for *Robinsonella mirandae* in Spmf and Mix litter in RCS and Spmf) were significant at $P < 0.1$ (Table 6.4 and Annex 6.2).

Table 6.4 Polynomial regression equations to describe variations in phosphorus over time in *Robinsonella mirandae* (a), *Robinsonella mirandae/Coffea arabica* (b), Mix litter (c) and *Mastichodendron capirii, Piper hispidum* and *Croton officinalis* in TCS, RCS and Spmf

System	Regression equation	R^2	ANOVA (F)	P
TCS (a)	P = 0.1361 + 0.000232 - 0.000001	43.1	6.81	0.006**
RCS (a)	P = 0.1304 + 0.000680 - 0.000003	45.7	7.58	0.004**
Spmf (a)	P = 0.1230 + 0.000329 - 0.000001	11.8	1.20	0.324^{ns}
TCS (b)	P = 0.1166 + 0.000979 - 0.000004	82.3	41.71	0.000***
RCS (b)	P = 0.1293 + 0.000931 - 0.000003	32.2	4.28	0.030***
Spmf (b)	P = 0.1034 + 0.001125 - 0.000004	66.4	17.80	0.000***
TCS (c)	P = 0.1125 + 0.000986 - 0.000004	74.3	26.03	0.000***
RCS (c)	P = 0.1244 + 0.000380 - 0.000001	16.4	1.76	0.200ns
Spmf (c)	P = 0.1167 - 0.000270 + 0.000001	25.1	3.01	0.075ms
Mastichodendron capirii	P = 0.09682 + 0.000450 - 0.000001	19.1	2.13	0.148ns
Piper hispidum	P = 0.08899 + 0.001267 - 0.000004	64.4	16.28	0.000***
Croton officinalis	P = 0.07729 + 0.000599 - 0.000002	27.3	3.39	0.056ms

ANOVA indicated that the P content of the leaf litter did not vary significantly within replicate samples, but did vary significantly between the litter type/systems and between the times of sampling (Annex Table 6.2). The interaction between time and litter type/system was significant. This implied that the changes in P content over time were not the same in each litter/system, but varied with respect to the different systems, as illustrated in Figures 6.2 ((a) and (b)) . Mix litter in Spmf (6.2 (c)) and *Mastichodendron capirii*, *Piper hispidum* and *Croton officinalis* (6.2 (d)) were characterized by low overall mean P contents < 0.12 whereas those in TCS and RCS and *Robinsonella mirandae*, *Robinsonella mirandae/Coffea arabica* in Spmf were characterized by higher overall mean P contents > 0.12.

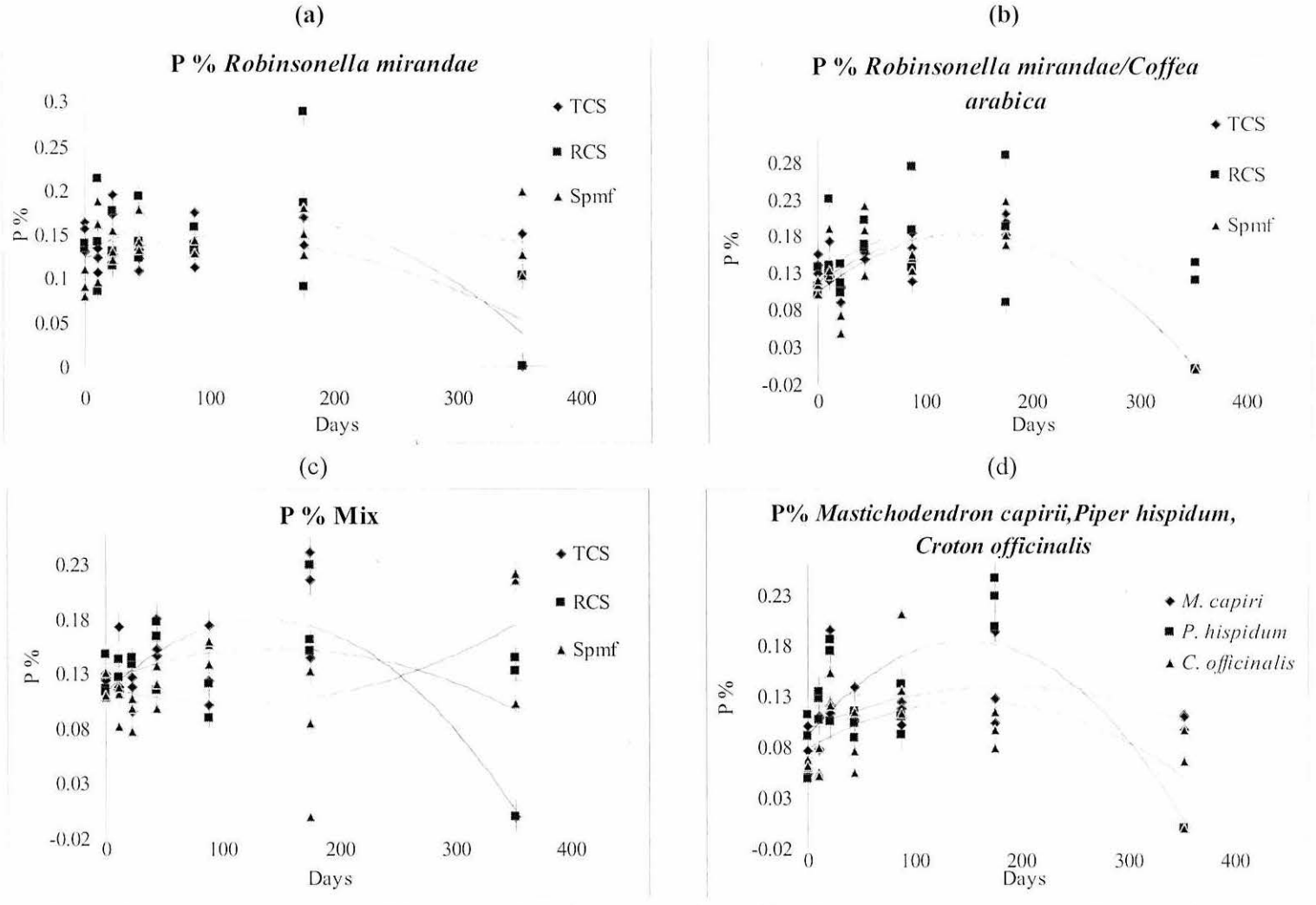


Figure 6.2 Regressions of P content of leaf litter over time in *(a).- Robinsonella mirandae; (b). - Robinsonella mirandae/Coffea arabica; (c).-Mix litter* and *(d).-Mastichodendron capirii, Piper hispidum and Croton officinalis* in TCS, RCS & Spmf.

6.3.3 Variations in the potassium content of the leaf litter over time

The changes in the K content of the leaf litters over time followed the same general pattern in all of the litter/systems (Figure 6.3 (a), (b), (c) and (d)). All the curves described a non-linear decline in the K content of the leaf litters with respect to time. There was no evidence for accumulation of K in the litter as observed for N and P. There was a rapid initial decline phase followed by a subsequent slower decline. The shapes of the curves varied between systems (Figure 6.3) and the different values of the regression coefficients (Table 6.5) indicated different rates of decline in the K content. All of the regression equations were significant at $P < 0.1$.

Table 6.5 Polynomial regression equations to describe variations in potassium over time in *Robinsonella mirandae* (a), *Robinsonella mirandae/Coffea arabica* (b), Mix litter (c) and *Mastichodendron capirii, Piper hispidum* and *Croton officinalis* in TCS, RCS and Spmf

System	Regression equation	R^2	ANOVA(F)	P
TCS (a)	K = 0.5529 - 0.002854 + 0.000004	40.4	6.10	0.009**
RCS (a)	K = 0.8374 - 0.003007 + 0.000002	33.5	4.54	0.025*
Spmf (a)	K = 0.5571 - 0.002649 + 0.000004	48.3	8.40	0.003**
TCS (b)	K = 0.6531 - 0.001650 + 0.000001	24.0	2.84	0.085ms
RCS (b)	K = 0.9826 - 0.004676 + 0.000006	42.0	6.51	0.007**
Spmf (b)	K = 1.628 - 0.01502 + 0.00003	71.7	22.84	0.000***
TCS (c)	K = 0.6034 - 0.004152 + 0.000007	37.6	5.42	0.014*
RCS (c)	K = 0.6522 - 0.003723 + 0.000006	44.2	7.12	0.005**
Spmf (c)	K = 1.419 - 0.01270 + 0.000026	33.1	4.45	0.027*
Mastichodendron capirii	K = 0.7186 - 0.005996 + 0.000013	25.7	3.11	0.069ms
Piper hispidum	K = 1.121 - 0.01158 + 0.000024	46.0	7.67	0.004**
Croton officinalis	K = 1.308 - 0.01073 + 0.000021	61.6	14.44	0.000***

ANOVA indicated that the K content of the leaf litters did not vary significantly within replicate samples, but did vary significantly between the litter type/systems and between the times of sampling (Annex Table 6.3). The interaction between time and litter type/system was significant. This implied that the changes in K content over time were not exactly the same in each litter, but varied with respect to the different systems, as illustrated in Figure 6.3. All leaf-litters in TCS, *Robinsonella mirandae* in Spmf, Mixed litter in RCS, and *Mastichodendron capirii* were characterized by lower overall mean K contents < 0.5 whereas those in *Robinsonella mirandae* (RCS), *Robinsonella mirandae/Coffea arabica* (RCS and Spmf) Mixed litter in Spmf, *Piper hispidum* and *Croton officinalis* were characterized by higher overall mean K contents > 0.5.

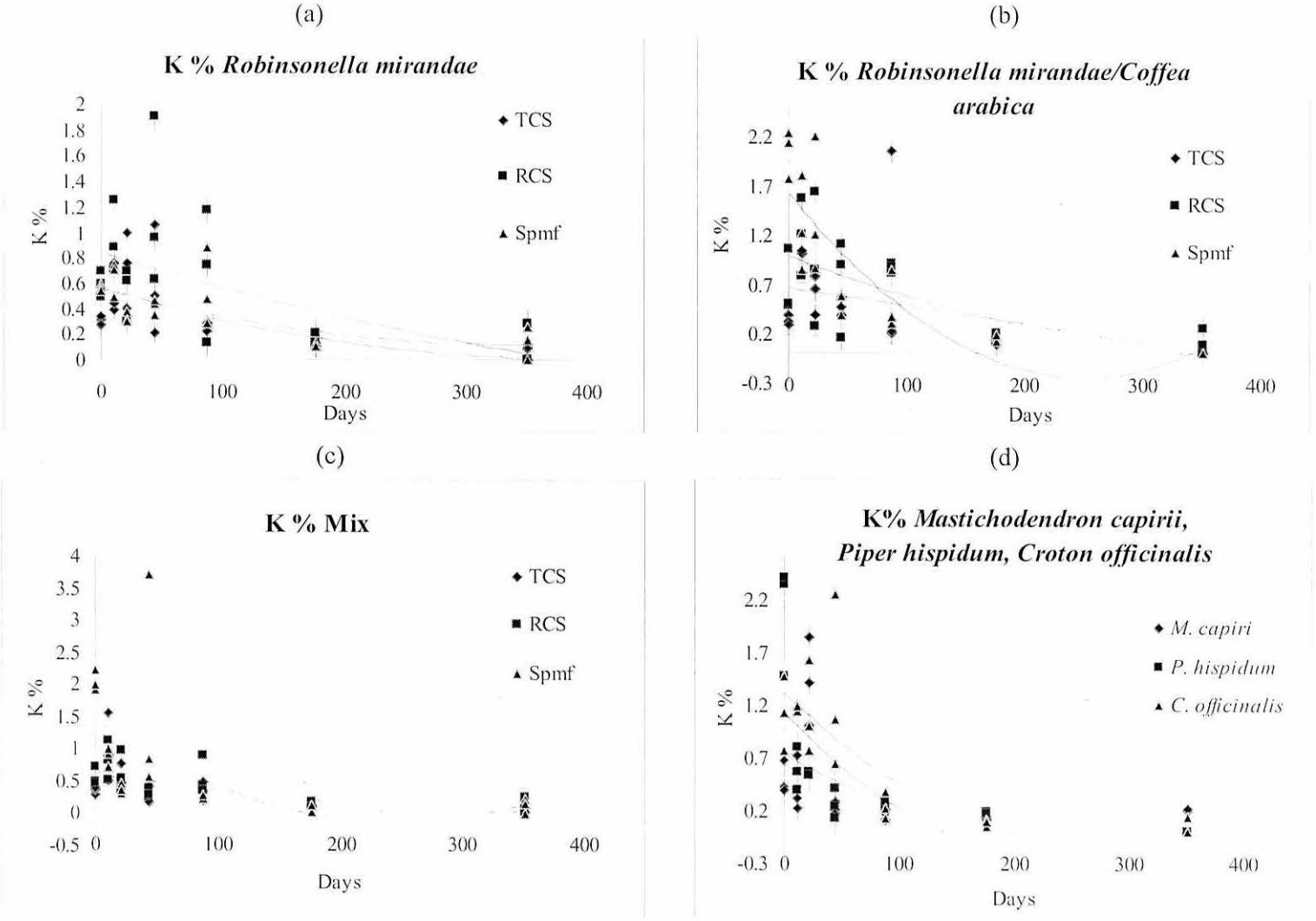


Figure 6.3 Regressions of K content of leaf litter over time in *(a).- Robinsonella mirandae; (b). - Robinsonella mirandae/Coffea arabica; (c).-Mix litter* and *(d).-Mastichodendron capirii, Piper hispidum and Croton officinalis* in TCS, RCS & Spmf.

6.3.4 Variations in the calcium content of the leaf litter over time

The changes in the Ca content of the leaf litters over time did not follow the same general pattern in all of the systems (Figure 6.4). Some of the curves (e.g. for *Robinsonella mirandae* (a) and Mixed litter in RCS (c)) described a progressive decline in the Ca content of the leaf litters with respect to time. Other curves (e.g. for all litter types in TCS (a, b, and c), Mixed litter in Spmf (c), *Mastichodendron capirii, Piper hispidum* and *Croton officinalis* (d)) were dome shaped, providing evidence for accumulation of Ca in the litter prior to a decline. The different shapes of the curves and the different values of the regression coefficients (Fig. 6.4 and Table 6.6 (a)) indicated different rates of decline in the Ca content. All but three of the regression equations were significant at $P < 0.1$ (Table 6.6). There was no significant change in Ca content with respect to time in the litters in *Robinsonella mirandae* (Spmf (a)) *Robinsonella mirandae /Coffea arabica* (b).

Table 6.6 Polynomial regression equations to describe variations in calcium over time in *Robinsonella mirandae* (a), *Robinsonella mirandae/Coffea arabica* (b), Mix litter (c) and *Mastichodendron capirii, Piper hispidum* and *Croton officinalis* in TCS, RCS and Spmf

System	Regression equation	R^2	ANOVA (F)	P
TCS (a)	Ca = 5.233 + 0.03046 - 0.000117	50.9	9.33	0.002**
RCS (a)	Ca = 4.612 + 0.003812 - 0.000038	57.6	12.24	0.000***
Spmf (a)	Ca = 3.800 + 0.00748 - 0.000022	2.6	0.24	0.791^{ns}
TCS (b)	Ca = 5.532 + 0.02926 - 0.000128	58.1	12.50	0.000***
RCS (b)	Ca = 5.234 - 0.00221 - 0.000013	21.4	2.46	0.114ns
Spmf (b)	Ca = 3.593 + 0.02176 - 0.000068	10.8	1.08	0.359ns
TCS (c)	Ca = 4.610 + 0.01667 - 0.000084	40.9	6.22	0.009**
RCS (c)	Ca = 4.688 - 0.03006 + 0.000061	43.5	6.92	0.006**
Spmf (c)	Ca = 3.517 + 0.02959 - 0.000113	52.9	10.11	0.001***
Mastichodendron capirii	Ca = 3.225 + 0.008522 - 0.000034	16.1	2.73	0.096ms
Piper hispidum	Ca = 5.473 + 0.04119 - 0.000165	55.7	11.30	0.001***
Croton officinalis	Ca = 2.656 + 0.01384 - 0.000044	18.5	3.04	0.059ms

ANOVA indicated that the Ca content of the leaf litters did not vary significantly within replicate samples, but did vary significantly between the litter types/systems and between the times of sampling (Annex Table 6.4). The interaction between time and system was significant. This implied that the changes in Ca content over time were not exactly the same in each system, but varied with respect to the different systems, as illustrated in Figure 6.4. Leaf litters in Mixed litter in RCS (Fig. 6.4 (c)) and Spmf, *Mastichodendron capirii* and *Croton officinalis* (Fig, 6.4 (d)) were characterized by lower overall mean Ca contents < 4.0 whereas *Robinsonella mirandae* in TCS and RCS (Fig. 6.4 (a)) and *Robinsonella mirandae/Coffea arabica* in TCS, RCS and Spmf (Fig. 6.4 (c)) as well *Piper hispidum* (Fig. 6.4 (d)) were characterized by higher overall mean Ca contents > 4.0.

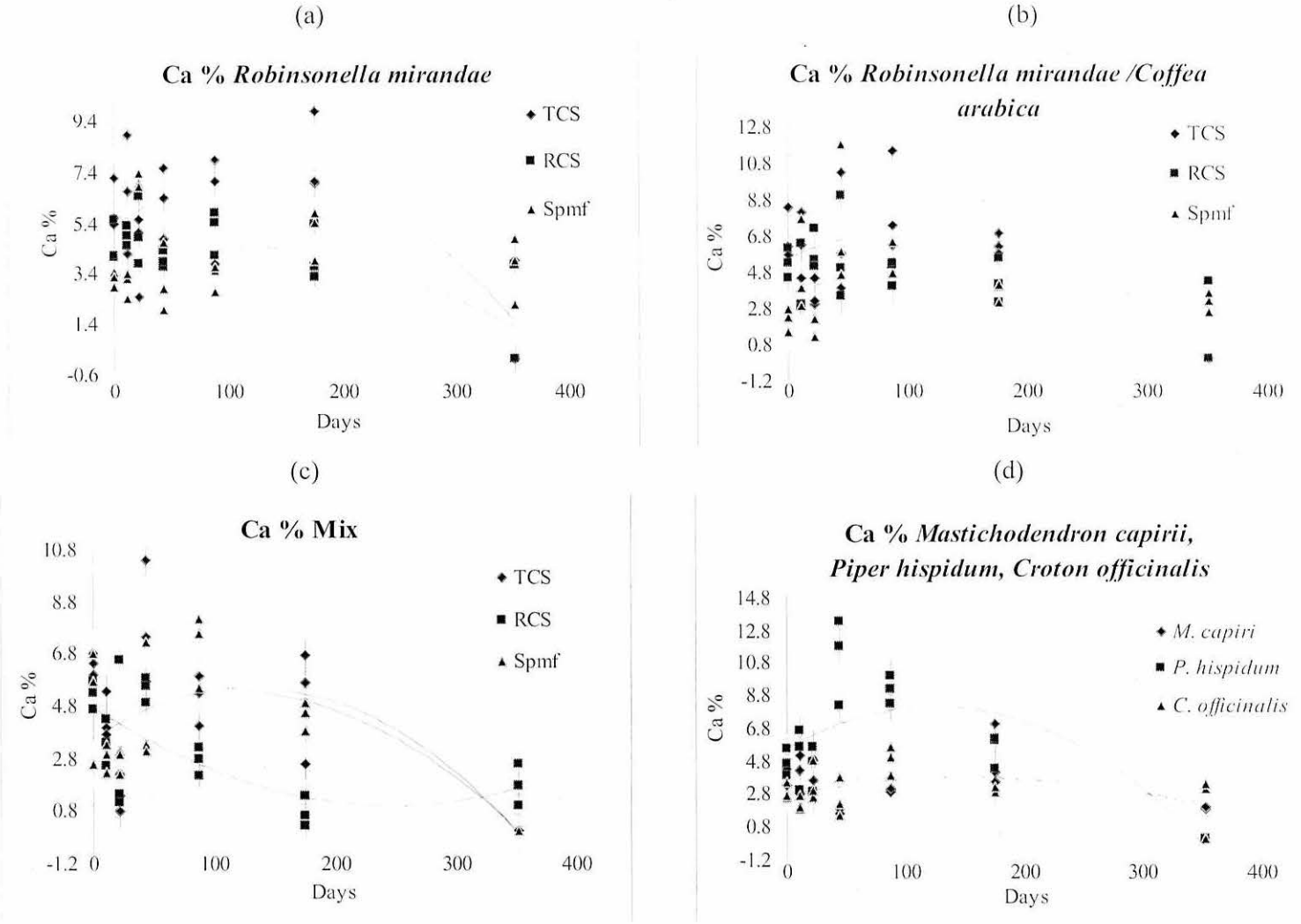


Figure 6.4 Regressions of Ca content of leaf litter over time in *(a).- Robinsonella mirandae; (b). - Robinsonella mirandae/Coffea arabica; (c).-Mix litter* and *(d).-Mastichodendron capirii, Piper hispidum and Croton officinalis* in TCS, RCS & Spmf.

6.3.5 Variations in the lignin content of the leaf litter over time

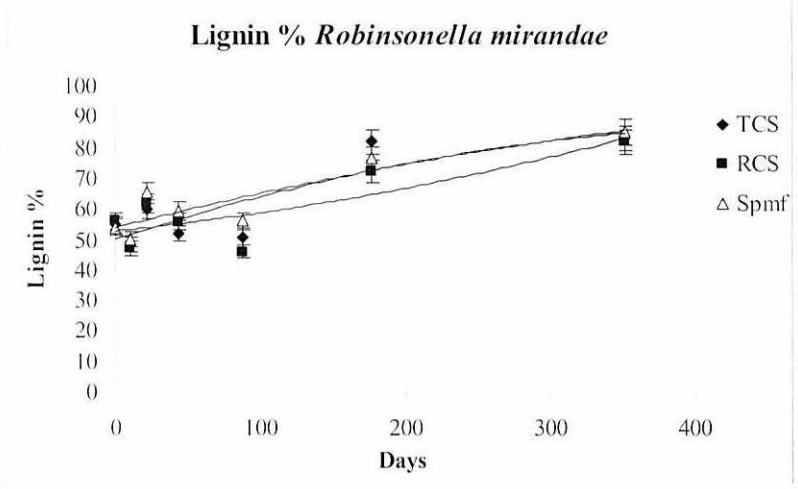
The changes in the lignin content of the leaf litters over time did not follow the same trend in all of the litter types/systems (Figure 6.5). In some leaf litters (e.g. in *Robinsonella mirandae* in TCS and Spmf (a), *Robinsonella mirandae/Coffea arabica* in TCS and RCS (b) and Mixed litter in TCS and Spmf (c)) there was no significant change in lignin content with respect to time (Table 6.7). For others (e.g. in *Robinsonella mirandae* (a) and Mixed litter in RCS (c), *Robinsonella mirandae/Coffea arabica* in Spmf (b) and *Mastichodendron capirii, Piper hispidum* and *Croton officinalis* (d)) the regression equations were significant at $P < 0.1$ and the curves were dome shaped, providing evidence for accumulation of lignin in the litter prior to a decline. The different shapes of the curves and the different values of the regression coefficients indicated different rates of decline in the lignin content.

Table 6.7 Polynomial regression equations to describe variations in ADL % over time in *Robinsonella mirandae* (a), *Robinsonella mirandae/Coffea arabica* (b), Mix litter (c) and *Mastichodendron capirii, Piper hispidum* and *Croton officinalis* in TCS, RCS and Spmf

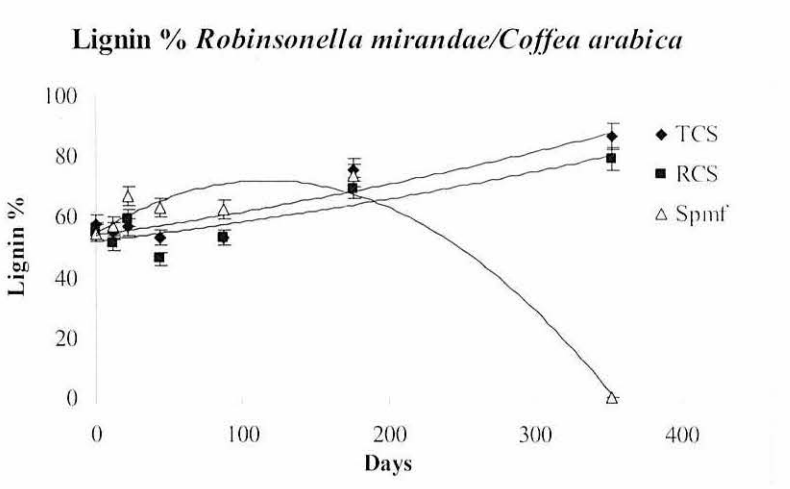
System	Regression equation	R^2	ANOVA (F)	P
TCS (a)	Lignin = -0.0002x2 + 0.1564x + 49.518	75.4	0.73	0.494^{ns}
RCS (a)	Lignin = 0.0001x2 + 0.049x + 52.346	69.2	15.89	0.000***
Spmf (a)	Lignin = -9E-05x2 + 0.1213x + 53.418	81.7	1.82	0.191^{ns}
TCS (b)	Lignin = 7E-05x2 + 0.0707x + 53.443	87.1	0.60	0.102ns
RCS (b)	Lignin = 7E-05x2 + 0.0566x + 51.539	78.5	0.64	0.538ns
Spmf (b)	Lignin = 0.0013x2 + 0.2983x + 54.275	96.0	3.98	0.037*
TCS (c)	Lignin = 5E-05x2 + 0.0966x + 49.064	81.9	2.20	0.104ns
RCS (c)	Lignin = 0.0001x2 + 0.0709x + 47.184	58.2	9.79	0.001***
Spmf (c)	Lignin = 0.0002x2 + 0.0363x + 49.966	29.4	2.98	0.076ms
Mastichodendron capirii	Lignin = 9E-05x2 + 0.0557x + 55.416	84.2	3.20	0.065ms
Piper hispidum	Lignin = -0.0012x2 + 0.2754x + 50.444	90.1	21.59	0.000***
Croton officinalis	Lignin = 0.0001x2 + 0.06x + 48.283	32.2	80.46	0.000***

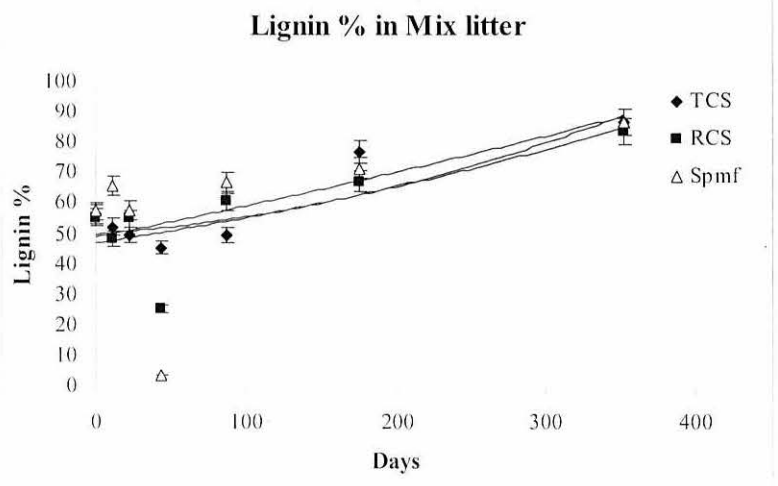
ANOVA indicated that the lignin content of the leaf litters did not vary significantly within replicate samples, but did vary significantly between the litter types/systems and between the times of sampling (Annex Table 6.5). The interaction between time and system was significant. This implied that the changes in lignin content over time were not exactly the same in litter, but varied with respect to the different systems, as illustrated in Figures 6.5. Leaf litters in TCS, *Robinsonella mirandae/Coffea arabica* and *Piper hispidum* were characterized by lower overall mean lignin contents < 0.1 whereas those litter in RCS, *Robinsonella mirandae* and Mixed litter in Spmf and *Mastichodendron capirii* and *Croton officinalis* were characterized by higher overall mean lignin contents > 0.1.

(a)



(b)





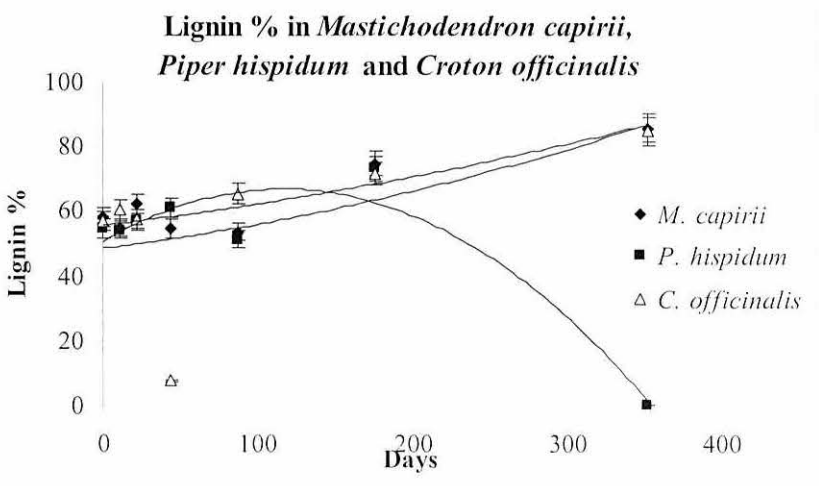


Figure 6.5 Regressions of ADL % (lignin content) of leaf litter over time in *(a).- Robinsonella mirandae; (b). - Robinsonella mirandae/Coffea arabica; (c).-Mix litter* and *(d).-Mastichodendron capirii, Piper hispidum and Croton officinalis* in TCS, RCS & Spmf.

6.3.6 Variations in the ADF% (cellulose) content of the leaf litter over time

The changes in the cellulose content of the leaf litters (ADF%) mostly followed the same general trend (Figure 6.6). All but one of the curves (for *Robinsonella mirandae/Coffea arabica* in Spmf (b)) described a decline in the cellulose content with respect to time. The regression coefficients for the second (squared) term of the equations were all zero, or close to zero, indicating that the declines in cellulose content were linear or approximately linear. The curve for *Robinsonella mirandae/Coffea arabica* in Spmf was dome shaped, providing evidence for an increase in cellulose in the litter prior to a decline. The different shapes of the curves and the different values of the regression coefficients indicated different rates of decline in the cellulose content in the litter in all the systems. All of the polynomial regression equations were significant at $P \leq 0.05$ (Table 6.8).

Table 6.8 Polynomial regression equations to describe variations in ADF% (cellulose) over time in *Robinsonella mirandae, Robinsonella mirandae/Coffea arabica, Mix litter and Mastichodendron capiri/Piper hispidum/Croton officinalis* in TCS, RCS and Spmf

System	Regression equation	R^2	ANOVA (F)	P
TCS (a)	Cel = -2E-05x2 + 0.0363x + 63.866	0.40	30.15	0.000***
RCS (a)	Cel = -0.0004x2 + 0.1846x + 65.229	0.77	14.00	0.000***
Spmf (a)	Cel = -3E-05x2 + 0.0383x + 67.541	0.46	36.62	0.000***
TCS (b)	Cel = 0.0002x2 - 0.0487x + 68.232	0.34	3.55	0.050*
RCS (b)	Cel = -0.0002x2 + 0.1031x + 68.359	0.71	8.50	0.003**
Spmf (b)	Cel = -0.0011x2 + 0.1922x + 63.603	0.96	93.59	0.000***
TCS (c)	Cel = 0.0001x2 - 0.0404x + 72.023	0.22	10.12	0.001***
RCS (c)	Cel = -0.0003x2 + 0.1354x + 67.642	0.68	23.42	0.000***
Spmf (c)	Cel = -0.0004x2 + 0.1537x + 73.002	0.65	5.30	0.016*
Mastichodendron capirii	Cel = -6E-05x2 + 0.046x + 69.095	0.69	12.86	0.000***
Piper hispidum	Cel = -0.0011x2 + 0.2239x + 62.658	0.96	23.81	0.000***
Croton officinalis	Cel = -1E-04x2 + 0.0516x + 77.538	0.63	18.43	0.000***

Cel= Cellulose

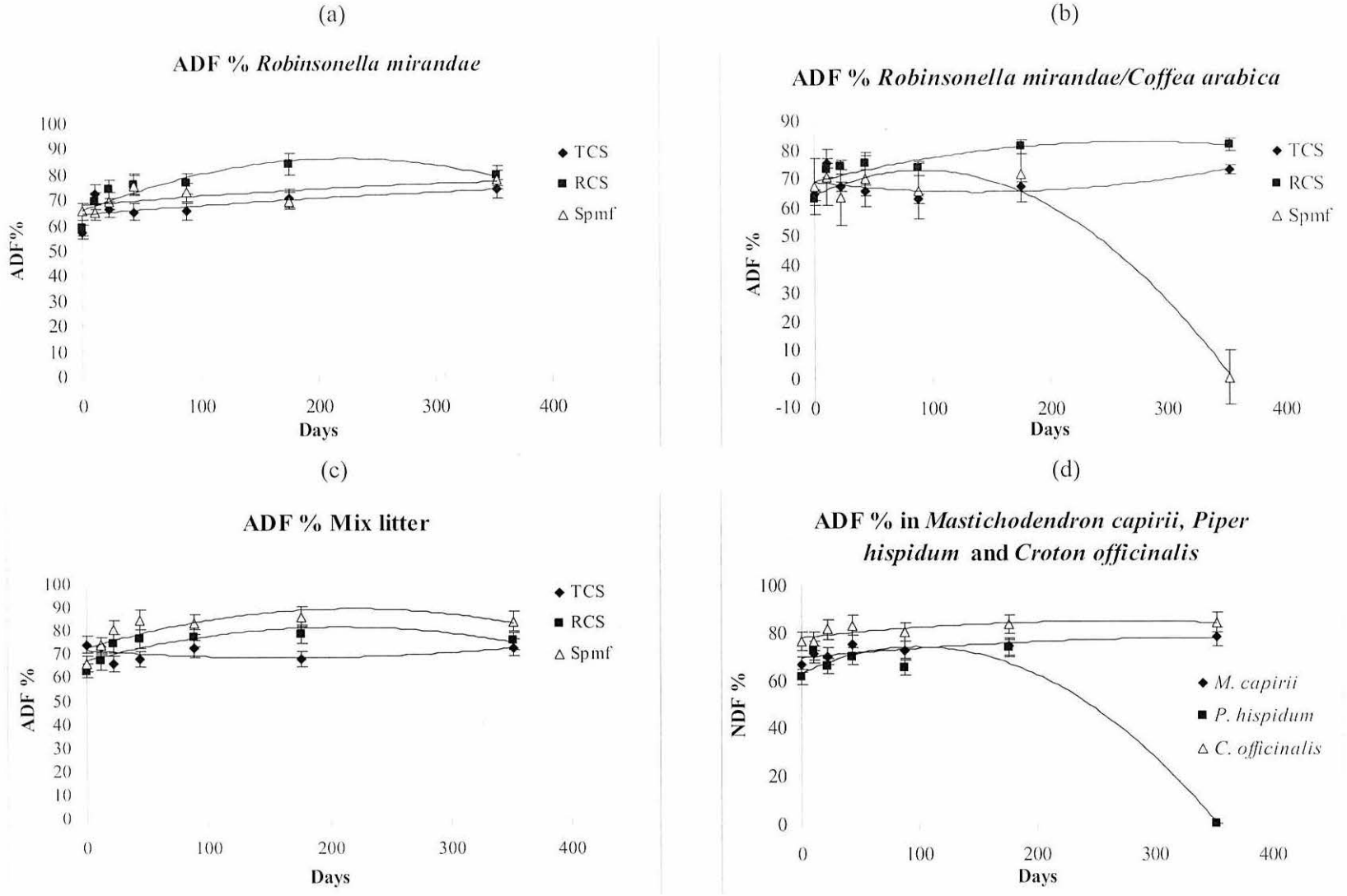


Figure 6.6 Regressions of ADF% (Cellulose content) of leaf litter over time in *(a).- Robinsonella mirandae; (b). - Robinsonella mirandae/Coffea arabica; (c).-Mix litter* and *(d).-Mastichodendron capirii, Piper hispidum and Croton officinalis* in TCS, RCS & Spmf.

ANOVA indicated that the cellulose content of the leaf litters did not vary significantly within replicate samples, but did vary significantly between the systems and between the times of sampling (Annex Table 6.6). The interaction between time and system was significant. This implied that the changes in cellulose content over time were not exactly the same in each system, but varied with respect to the different litter/systems, as illustrated in Figure 6.6. Leaf litters in *Robinsonella mirandae* (TCS), *Robinsonella mirandae/Coffea arabica* (Spmf), *Mastichodendron capirii* and *Piper hispidum* were characterized by lower overall mean cellulose contents < 0.07 whereas those in the other litter in RCS, Spmf and *Croton officinalis* were characterized by higher overall mean cellulose contents > 0.07.

6.3.7 Variations in the NDF % (hemicelluloses) content of the leaf litter over time

The changes in the hemicelluloses content of the leaf litters mostly followed the same general pattern as the changes in cellulose (Figure 6.7). All of the curves described progressive declines in the hemicelluloses content with respect to time. The regression coefficients for the second (squared) terms of the equations were all zero or close to zero, indicating that the declines in hemicelluloses were linear or approximately linear over time. Different values of first the regression coefficients reflected differences in the rates of decline of hemicelluloses content in the litter and systems. All of regression equations were significant at $P \leq 0.05$ (Table 6.9).

Table 6.9 Polynomial regression equations to describe variations in NDF % (hemicelluloses) over time in *Robinsonella mirandae* (a), *Robinsonella mirandae/Coffea arabica* (b), Mix litter (c) and *Mastichodendron capirii, Piper hispidum* and *Croton officinalis* in TCS, RCS and Spmf

System	Regression equation	R^2	ANOVA (F)	P
TCS (a)	HCel = -0.0002x2 + 0.041x + 57.144	0.34	8.73	0.002**
RCS (a)	HCel = -4E-05x2 + 0.0004x + 57.461	0.16	12.23	0.000***
Spmf (a)	HCel = 0.0002x2 - 0.0898x + 55.582	0.26	7.54	0.004**
TCS (b)	HCel = 2E-05x2 - 0.0081x + 53.289	0.004	8.34	0.003**
RCS (b)	HCel = -6E-05x2 + 0.0505x + 53.914	0.87	13.81	0.000***
Spmf (b)	HCel = -0.0007x2 + 0.1285x + 48.707	0.88	96.87	0.000***
TCS (c)	HCel = 3E-06x2 - 0.0124x + 54.458	0.74	6.71	0.007**
RCS (c)	HCel = -0.0003x2 + 0.0933x + 51.595	0.62	12.72	0.000***
Spmf (c)	HCel = -0.0002x2 + 0.0832x + 57.522	0.58	16.10	0.000***
Mastichodendron capirii	HCel = -0.0002x2 + 0.0578x + 52.348	0.15	5.69	0.012*
Piper hispidum	HCel = -0.001x2 + 0.2232x + 42.452	0.96	7.37	0.005**
Croton officinalis	HCel = -4E-05x2 + 0.024x + 56.393	0.21	9.61	0.001***

Note: Hcel= Hemicellulose

ANOVA indicated that the logt hemicelluloses content of the leaf litters did not vary significantly within replicate samples, but did vary significantly between the litter/systems and between the sampling dates (Annex Table 6.7). The interaction between time and system was significant. This implied that the changes in hemicelluloses content over time were not exactly the same in each system, but varied with respect to the different systems, as illustrated in Figure 6.7. Leaf litters in RCS, Mixed litter in Spmf and *Mastichodendron capiri, Piper hispidum* and *Croton officinalis* were characterized by lower overall mean hemicelluloses contents < 0.7 whereas those in all the other litter were characterized by higher overall mean hemicelluloses contents ≥0.7.

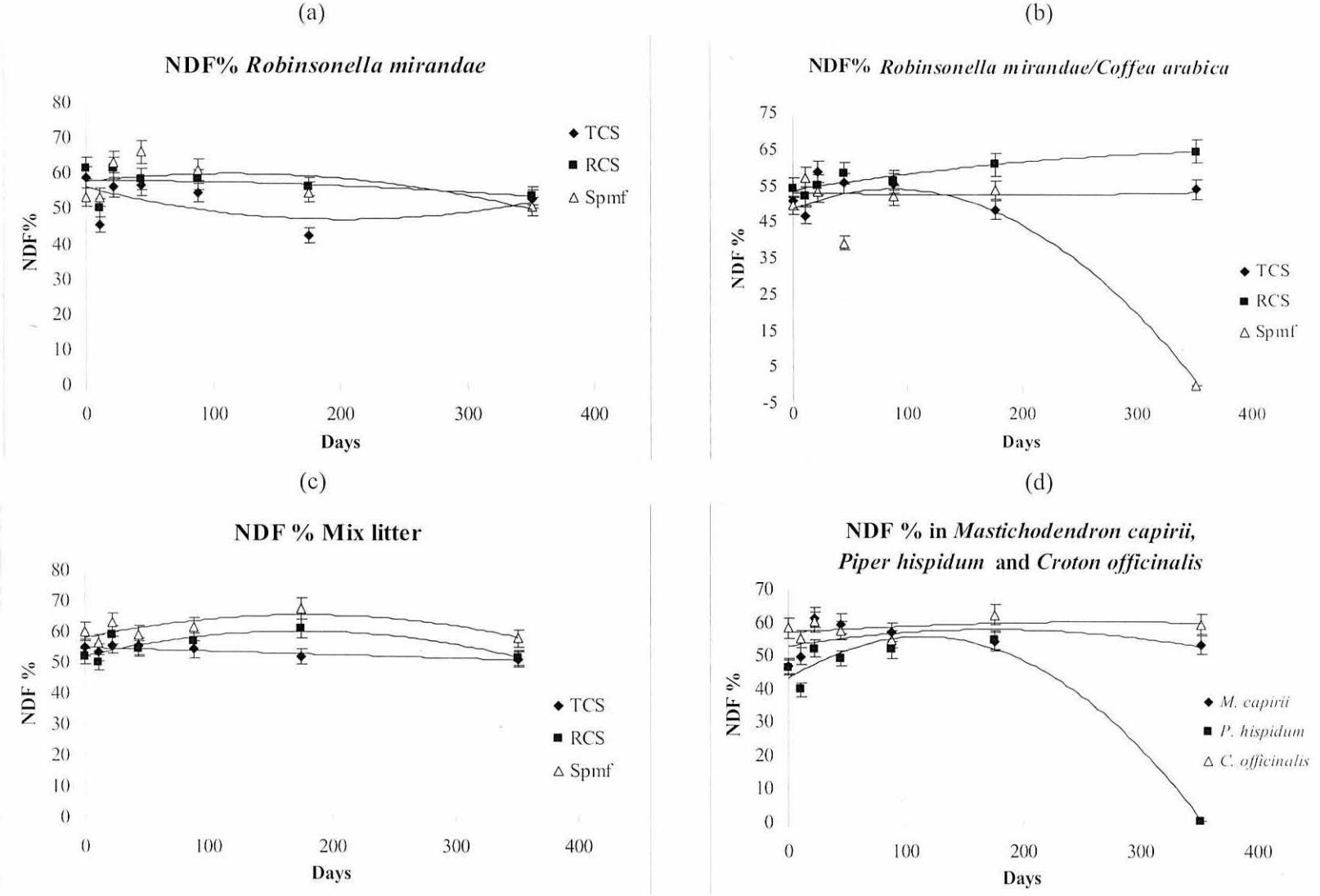
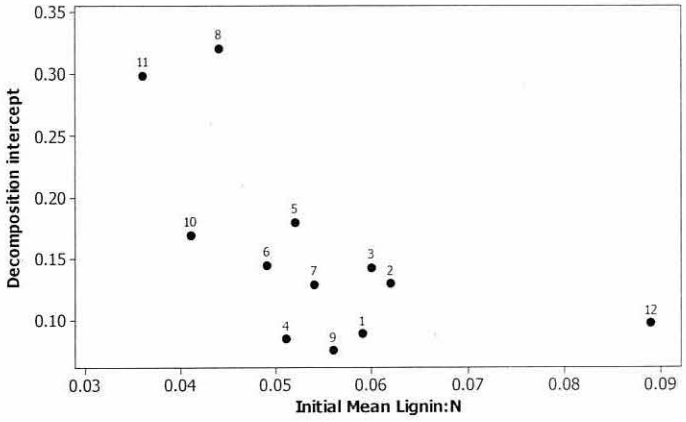


Figure 6.7 Regressions of NDF% (hemicelluloses content) of leaf litter over time in *(a).- Robinsonella mirandae; (b). - Robinsonella mirandae/Coffea arabica; (c).-Mix litter* and *(d).-Mastichodendron capirii, Piper hispidum and Croton officinalis* in TCS, RCS & Spmf.

6.3.8 Correlation between decomposition rates and Lignin:N and C:N ratios

The regression coefficients used to describe the changes in the decomposition rates (Table 6.2 (b)) were plotted against the initial Lignin:N ratios (Table 6.2 (a)) for the litter in the three systems (Figure 6.8). The initial rates of increase in decomposition (indicated by the intercepts) were highest for the high quality litters (e.g. *Robinsonella mirandae/Coffea arabica* in Spmf, *Mastichodendron capirii* and *Piper hispidum*) whilst moderate and low quality litters exhibited lower initial rates of increase in decomposition (e.g. *Croton officinalis*).

(a)



(b)

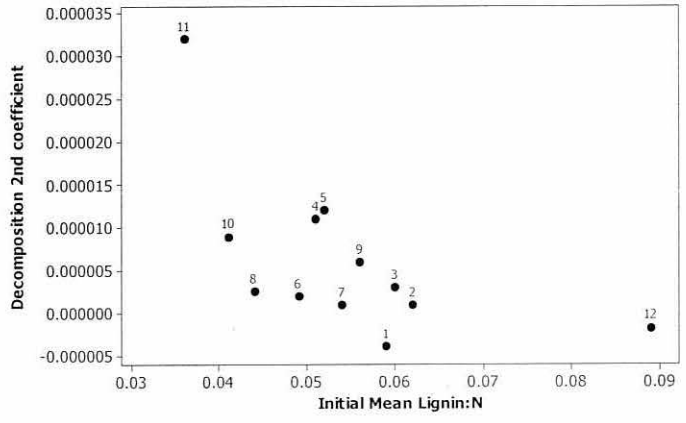
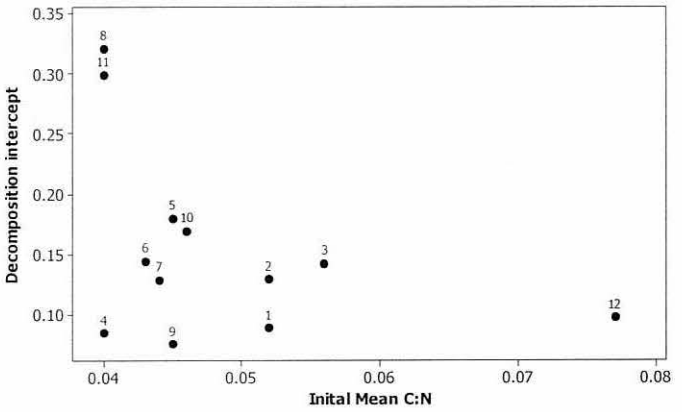


Figure 6.8 Relationships between the decomposition rates and leaf litter quality (initial Lignin:N ratio) in *Robinsonella mirandae* (1,4,7), *Robinsonella mirandae/Coffea arabica* (2,5,8) and Mix litter (3,6,9) in TCS, RCS and Spmf respectively and *Mastichodendron capirii* (10), *Piper hispidum* (11) and *Croton officinalis* (12).

A slowing down of the rates of decomposition (indicated by a negative value for the second regression coefficient) occurred after 200 days in the lowest quality litter (*Croton officinalis*) so the plot of decomposition on time in this system was dome shaped (Figure 6.8). In contrast, the second regression coefficients were high and positive for the better quality litters (e.g. *Robinsonella mirandae/Coffea arabica* in Spmf, *Mastichodendron capirii* and *Piper hispidum*) so that decomposition continued to increase with respect to time over the sampling whole period, and the curves did not slope downwards after 200 days (Figure 6.8).

(a)



(b)

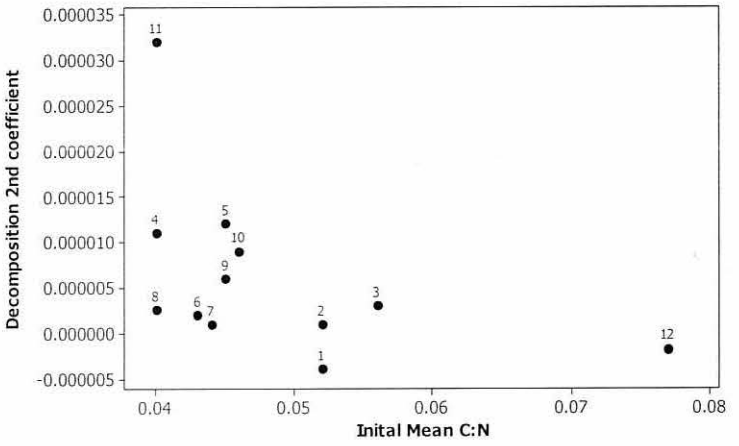


Figure 6.9 Relationships between decomposition rates and leaf litter quality (initial C:N ratio) in *Robinsonella mirandae* (1,4,7), *Robinsonella mirandae/Coffea arabica* (2,5,8) and Mix litter (3,6,9) in TCS, RCS and Spmf respectively and *Mastichodendron capirii* (10), *Piper hispidum* (11) and *Croton officinalis* (12).

The coefficients of the polynomial equations which described the changes in the decomposition rates over time (Table 6.2 (b)) were also plotted against the initial C:N ratios (Table 6.2 (a)) for the litter tested in the three systems (Figure 6.9) and similar patterns were revealed to those in Figure 6.9. The initial rates of increase in decomposition (indicated by the intercepts) were higher for the best quality litters (e.g. *Robinsonella mirandae/Coffea arabica* in Spmf, *Mastichodendron capirii* and *Piper hispidum*) and lower for the medium and lower quality litters. The rates of increase in decomposition (indicated by the negative value for the second regression coefficient) slowed down for the lower quality litters (e.g. *Croton officinalis*) but the decomposition rate remained high for the best quality litters (e.g. *Mastichodendron capirii* and *Piper hispidum*). Considerable variations in the patterns of change in the chemical constituents of the leaf litter with respect to time and system were revealed by this investigation. A comparison of the extremes (i.e. the lowest quality leaf litter with the highest quality leaf litters) is performed here, in order to examine whether litter quality was a causative factor for such variations.

6.4 Discussion

Leaf litter quality is fundamental in determining rates of decomposition and the turnover of nutrients in forest systems (Melillo et al. 1982, 1989, 1993; McClaugherty et al., 1982 and 1985; Palm and Sanchez, 1990; Scott and Binkley, 1997; Loranger et al., 2002). This study corroborated this idea and identified several factors influencing leaf decay.

The parameters that best explained the variability were N, P and Lignin:N and C:N ratios. *Robinsonella mirandae, Robinsonella mirandae/Coffea arabica* and Mix litter of various sites differed in its initial concentrations of N (TCS<RCS<Spmf), and for Lignin:N and C:N ratios (RCS<Spmf<TCS) providing proof that the nutrient initial concentrations determined decomposition rates in the initial phase.

Lignin concentration didn't provide any proof of their influence on first decomposition stages but in agreement with other studies as the Lignin:N (Melillo et al, 1982) and C:N ratios (Swift et al, 1979) increase, these have a bigger influence on the rates of decomposition in agreement with other studies where nutrient concentration ha.

As Meentemeyer (1978), Meentemeyer et al. (1982) and Palm and Sánchez (1990), stated that the higher nutrient content the faster the decomposition can be, that is corroborated by the high rates of decomposition showed by *Piper hispidum, Mastichodendron capirii* and *Robinsonella mirandae/Coffea arabica* litter in contrast to the low quality leaf litter values shown by *Croton officinalis* and therefore lower decomposition rates over time.

The rest of the litter obtained medium nutrient quality values and it is shown as well in the decomposition rates (Alvarez-Sanchez and Becerra-Enriquez (1996); González and Seastedt; 2001). Alvarez-Sánchez y Becerra, (1996) studied the nutrient content in some tree species leaves in a rain forest (Mexico) and observed that the species with lowest nutrient concentration values for Mg, K, Ca and P had the lowest decomposition rates. In this study the low quality litter (*Croton officinalis*) showed low nutrient content for N, P, and Ca but high for K, Lignin and Celluloses, and had the lowest decomposition rates of the litter tested.

The changes in the quality parameters over time followed the same pattern in the three systems and the litter tested. During the experiment it was possible to observe that an initial phase of the decomposition process N and P correlates well with decomposition over time (0 to 176 days) than other chemical parameters and this is in agreement with Aerts and De Caluwe (1994), and is characterized by an accumulation of N that possibly indicates immobilization by the soil microorganisms. This happens mainly during the months of the dry season, as found by Parton et al. (2007), but after 176 days lignin and hemicelluloses seems to have more influence and presence in the patterns of the chemical composition changes in the leaf litter and loss of weight. Güsewell and Gessner (2009), stated that between 27 and 96% of decomposition depends on the N and P content of the leaves. Higher initial content of high quality litter (eg. *Robinsonella mirandae/Coffea arabica* in Spmf and *Piper hispidum*) and the N concentration is correlated with P concentration promoted decomposition as is suggested by other authors (Kumar and Deepu, 1992, Eviner et al., 2006).

The correlations between N and P concentrations suggest that nutrient release influenced each other during litter decomposition (Kwabiah et al, 2001). The N

dynamics were more significantly correlated with P during the first phases of decomposition in litter with initial high N and P concentrations.

These results also seem to endorse some other investigations (Aber et al, 1990) which suggest decomposition processes are divided into two phases (Xuluc-Tolosa et al., 2003; Zhou et al., 2008) in which, during the first phase, it happens a process of immobilization of the nutrients, mainly of N and P and a releasing of nutrients, which can be controlled by different factors but probably in the case of tropical forests, precipitation and temperature are a determining factors (Meetenmeyer, 1978; Aerts, 1997; Trofymow et al., 2002) in the second phase the more recalcitrant components influence the rates of decomposition (Aber and Melillo, 1980; Chadwick et al., 1998; Preston and Trofymow, 2000).

In this investigation, the limit between the two processes was the beginning of the rainy season, at the end of May and first week of June until the month of October. The greatest precipitation occurred during the months of July and August, in which a major leaching of soil nutrients of the forest can occur, but the rates of decomposition slowed down in comparison to the first stage of the decomposition process.

Xuluc-Tolosa et al (2003) indicate that the difference between systems does not have an important additive effect on decomposition, but the decay rates of the individual species associated with time varied considerably. The leaf litter mixes were chosen as representatives of the different systems studied: Traditional coffee system (TCS) Rustic coffee system (RCS) and Spmf, these include a representative species per system: *Mastichodendron capirii* (TCS) *Piper hispidum* (RCS) and *Croton officinalis* (Spmf).

Other possible causes to explain the variability in the rates of decomposition can be the additive or non-additive responses of mixed litter decomposing on the forest floor. Many studies have found that the litter can decompose faster than expected when the component species differ in their litter quality nutrient concentration (Wardle et al., 2002; Quested et al., 2003). The additive effect can manifest itself in the increase of the decomposition rates when litter of high quality influence the other litter deposited on the forest floor (Wardle et al 1997; Scowcroft, 1997), through the release of N and P which contributes to the general source of energy for the decomposer colonies

micro-organisms. This could be the case of the litter represented in this study of *Robinsonella mirandae*, and *Piper hispidum*. A negative additive effect can happens when litter with low concentrations of N and high Lignin:N ratios affect the rest of the litter deposited on the forest floor, some examples in this study are the leaf litter of *Croton officinalis*, and the mix of *Robinsonella mirandae/Coffea arabica* in RCS.

The mixture of different litter species with different resource quality and leaf structure change the chemical environment and alter physically the total area where occur the decomposition process (McArthur et al., 1994; Hector et al., 2000; Gartner and Cardon, 2004). These alterations can affect as well the abundance and activity level of the decomposer organisms (Hansen and Coleman, 1998; Wardle et al., 2002). Therefore, the physical and chemical changes in litterfall mixed, can influence the rates of decomposition of direct and indirect way (by means of the descompositor community and its activities).

In this study, it seems that the litter mixes didn't have an important effect on the decomposition rates apart from the RCS mix, in which it could be that *Piper hispidum* could have an important effect in accelerating the decomposition in situ (Table 5.1 and 5.2), and probably in the case of the high quality litter mixes in the TCS and Spmf that showed fast decomposition rates during the first phase of decomposition but possibly slowered over time because of the accumulation of more recalcitrant chemical components such as lignin or hemicelluloses. Negative interactions can occur when one of the main components of litter mixtures contains high amounts of more recalcitrant and resistant compounds such as lignin, phenolics (Hättenschwiler and Vitousek, 2000) slowing down the decomposition of the entire litter mixture (Hoorens et al., 2003).

In general for perennial species it is known that generally they display a greater amount of lignin and phenols, which produces a slow decomposition but that in the deciduous species and by consequence a smaller liberation of nutrients, besides to inhibit other processes (as the germination of other species in the system). These conditions could be part of a strategy of nutrient saving and dominance for evergreen species, as soon as for the deciduous species could perhaps be translated as of survival. This implies that the characteristics of the perennial species not only reduce

the waste of nutrients, but that also can produce better conditions in the soil to medium and long term in the fertility of the soil, also regulating with it, the competitive balance between the perennial and deciduous species. Shade-grown coffees are agricultural systems that contain some forest-like characteristics.

6.5 Conclusions

Leaf litter quality parameters can be a fundamental tool for determining the rates of decomposition and turnover of nutrients in agro-ecosystems and natural forest systems (Melillo et al., 1982; Melillo et al., 1989; Palm and Sanchez, 1990; Loranger et al., 2002). This study showed the importance of determining these parameters and identified other factors influencing leaf decay.

The parameter that best explained the variability of the decomposition rates through time was N, P, followed by the Lignin:N ratio with some differences of decomposition in the RCS followed by TCS and Spmf.

The lowest quality leaf litter was *Croton officinalis* in the forest system. This litter was characterized by:

- Low initial N, P, Ca and Hemicelluloses, but high initial K, lignin and cellulose (Table 6.2(b))
- High initial Lignin:N and C:N ratios (Table 6.2 (a)).
- An initially high decomposition rate, which slowed down to zero over time (Figure 6.9 and 6.10).
- An initial small increase in N and P followed by a rapid decrease (Figures 6.1 & 6.2).
- A rapid non-linear decline in K to zero (Figure 6.3)
- A small (marginally significant) change in Ca (Figure 6.4).
- A small increase in Lignin followed by a rapid decline (Figure 6.5).
- Progressive declines in cellulose and hemicelluloses which were approximately linear with respect to time (Figures 6.6 & 6.7)

All these characteristics corroborates the results obtained by Montagnini et al. (1993), Briones and Ineson (1996) and Wardle et al. (1997 and 2002), which showed a slower

rate in decomposition of lower quality litters, probably as a result of a longer concentration of more recalcitrant components and less N compounds as a source of energy for soil micro-organisms in the soil.

The highest quality leaf litters, with the lowest initial Lignin:N and C:N ratios (Table 6.2 (a)) were: *Robinsonella mirandae/Coffea arabica* in the Spmf, *Mastichodendron capirii* in the TCS and *Piper hispidum* in the RCS. These high quality litters were characterized by:

- Low initial Lignin:N and C:N ratios (Table 6.2 (a));
- Decomposition rates which increased continuously with respect to time (Figure 6.8 & 6.9).
- An initial rapid accumulation of N and P followed by a progressive decline with time (Fig 6.1 & 6.2).
- A rapid decline in K (Figure 6.3)
- No significant change in Ca, or an increase, followed by a slow decline (Figure 6.4).
- An increase in lignin to an asymptote, or an increase followed by a slow decline (Figure 6.5)
- Progressive declines in cellulose and hemicelluloses which were approximately linear with respect to time (Figures 6.6 & 6.7)

It is concluded that the overall chemical changes which took place in leaf litters of different quality were relatively similar; however, significant differences were observed between the relative rates at which different qualities of litter decomposed, and between the trends and patterns in the chemical changes with respect to time.

These results support the hypothesis that the quality of leaf litter can influence overall decomposition rates within mixtures, through the transfer of nutrients and secondary chemicals and recalcitrant compounds among litter types or by the influence of the decomposer micro-organisms colonies (Chapman et al., 1988; Taylor et al., 1989; McTiernan et al. 1997; Wardle et al. 1997 and 2002; Salamanca et al. 1998; Hector et al. 2000; Xuluc-Tolosa et al., 2003) and climate (Taylor and Jones, 1990; Aerts, 1997).

It is hypothesized that variations in the rates of various decomposition processes (e.g. mobilization, accumulation, mineralization, and leaching of chemical constituents) and possibly variations in environmental factors (e.g. differences in temperature, humidity and rain) were probably responsible for the significant differences observed between the chemical constituents of the litters in the three systems over the 352 day period of observation. These hypotheses are testable by further research.

Regression analysis and ANOVA (Annex) confirmed that the decomposition rates and chemical constituents of the leaf litters varied with respect to both the time of sampling and to the systems where the litter bags were incubated. The results also confirmed the hypotheses that variations in decomposition rates and chemical constituents were associated with different qualities and taxonomic compositions of leaf litters. Lignin:N ratio.

Chapter 7 Soil nutrients: Does the litter quality have an important effect in the changes of the soil of TCS, RCS and Spmf?

7.1 Introduction

Beside the climate, soils are the second most important factor in controlling the distribution and composition of tropical forests. Richards (1953), Nye and Greenland (1964) and Sanchez-Vera et al. (2003), stated that soil nutrient pools in soils of Latin-America were poor in most of tropical forests, but Proctor (1983), Proctor et al., (1983), listed characteristics of different soil types in the tropics, that included countries as Malaysia, Ghana, Venezuela, Peru and Brazil, and concluded that no generalization can be made over nutrient pools in tropical forests.

The macronutrients are considered to be in low quantities in tropical soils with most of these nutrients coming from net primary productivity, dust, rain and other organic remainders. Nitrogen is the most limiting nutrient in soils and its availability depends on important soil processes of mineralization and immobilization. The N mineralization which is basic for N availability to the plants is the process in which organic N is transformed into mineral N, mediated by some bacteria colonies as *Nitrosomes* and *Nitrosobacter*. This process is favoured by high or warm temperatures, high soil moisture and pH close to neutral and with good aeration. The other process is immobilization which is the transformation of mineral N into organic N through the microbial tissues and it can occur as a result of a high C: N ratio of the organic matter deposited on the forest floor. As a result of the microbial metabolism of the soil organic matter, some compounds of N, P and S are available to the plants in the system. The N and P cycles have a synergistic effect when acting on the soil and can be important for effective N cycling (Castellanos et al, 2000).

7.1.1 Soil types in México.

The sol types and characteristics are already mentioned in pages 30-31.

General objective

The general objective of this chapter was to describe the soil condition and analyze the chemical properties in TCS, RCS and Spmf. The soil nutrients and characteristics

analyses in this study were, total N, P, K, Ca, pH and O.M. % It was expected to find lower values in N, P, K but higher in Ca because of the origin of the soil. About organic matter it was expected to find differences between the three study systems and over the time. The hypothesis was that changes in nutrient concentration over time will take place over time as effect of the climatic factors and litter decomposition processes on the soil.

7.2 Materials and methods

7.2.1 Research site (See chapter 4 for sampling sites)

7.2.2 Soil sampling and laboratory analyses

During January and December 2006, 126 soil samples were taken from the same sites as the leaf litter samplings and litterbag collections (see Chapter 4). The sampling intervals were the same as for the litterbag collections (0, 11, 22, 44, 88, 176 and 352 days) from the month of January to December 2006. From the sampled sites, the forest floor surface was cleared of litterfall and organic matter and a trowel was used to dig a hole of 40 cm depth and 30 cm wide in order to extract samples from at two depths (0 to 15 cm and 15 to 30 cm). The soil samples were collected in black polythene bags, sealed and labelled and were sent immediately to the soil laboratories (Laboratorio de Suelos Universidad Autonoma de Chapingo) to be stored to perform analyses of nutrient and S.O.M.

Soil laboratory analyses

The soil was processed before the analyses by oven drying the samples at a temperature of 60°C for 48 hours, and then it was ground until it passed through a 3 mm mesh (Dominguez, 1999). The following analyses were performed at the soil laboratory in duplicate:

pH: pH potentiometer relation soil-water 1:2, in H2O and in 1 M KCl solution.

Soil Organic Matter: Soil organic matter percentage content was determined by the method of Walkley and Black. This procedure estimates only partially the organic soil C oxidation with potassium dichromate and is necessary to use a correction factor to

calculate the difference between the 77% of the organic Carbon that is oxidated in soil and the and 58 % of Carbon that the organic matter contains (Aguilar and Heil, 1988; Castellanos et al. 2000).

Total Nitrogen (N): The samples were digested with sulphuric acid, distilled in boric acid and determined by titration with 0.1 M sulphuric acid (Kjeldahl digestion);

Phosphorous (P): *Olsen and **Bray-1 methods

***Olsen method.** This was used when the upper reporting limit was 100 ppm. One gram scoop of soil and 20 millilitres of 0.5 molar sodium bicarbonate ($NaHCO_3$) solution was shaken for 30 minutes. Blue colour in the filtered extract is developed with successive additions of an ammonium molybdate-sulfuric acid solution and then an ascorbic acid solution and measured with a fiber optic probe colorimeter at 882 nm.

****Bray P-1 method.** This method was used to measure smaller P quantities when the upper limits were 50 ppm. It has been shown to be effective in calcareous and neutral soils (Castellanos et al, 2000). Phosphorus was extracted by a solution consisting of 0.025 normal HCl and 0.03 normal NH_4F and referred to as Bray-1 extractant. One gram scoop of soil and 10 millilitres of extractant were shaken for 5 minutes. The amount of phosphorus extracted is determined by measuring the intensity of the blue colour developed in the filtrate when treated with ammonium molybdate-hydrochloric acid solution and then amino-naphthol-sulfonic acid solution. The colour is measured by an absorption spectrophotometer at 640 nm.

Potassium (K) and Calcium (Ca): Exchangeable cations were extracted by 1 N Ammonium acetate and by centrifugation for 5 min. at 2,500 rpm (extractants 1.0N, pH 7.0, 1:2 Relation and determined by Spectrometry Flame Emission);

7.2.3 Statistical analysis

The statistical tests conducted were Analyses of Variance using Genstat (Pallant, 2004) including a Tukey test applied for the data collected in the three systems (TCS, RCS and Spmf), are Pearson's correlation (Pallant, 2004). Polynomial regressions were done with Excel (2007) to observe the prediction of the nutrient concentrations

in soil over time in each of the studied systems. The aim of the statistical analysis was to determine if the soil chemistry varied in different systems (TCS, RCS and Spmf) and to investigate the relationships between the temporal variations in soil chemistry and the decomposition rates of the leaf litter. The data were obtained from the three systems at two different depths (0-15 and 15-30 cm), which all produced "medium quality" litters (Table 6.1). The soil chemistry variables were N (Nitrogen), P (Phosphorus), K (Potassium), Ca (Calcium), S.O.M. (% Organic Matter) and pH.

7.3 Results

7.3.1 Initial conditions

One-Way ANOVA indicated that the mean initial (Day 0) N, P, K, Ca, OM, and pH of the soils did not vary significantly between the 3 systems and depths (Table 7.1). The soils were all circum-neutral in pH with low to moderate inorganic nutrient and organic matter content.

Table 7.1 Initial (Day 0) soil chemistry variables (mean ± SD) in TCS, RCS and Spmf (0-15 and 15-30 cm depth)

System	N (mg/kg)	P (mg/kg)	K (mg/kg)	Ca (mg/kg)	S.O.M. (%)	pH
TCS 0-15	16.07±2.19	18.80±23.3	899±741	8899±1228	35.87±5.65	6.67±0.28
TCS 15-30	17.30±4.33	4.15±2.55	323±101	9893±383	13.89±2.79	7.18±0.50
RCS 0-15	14.80±0.00	19.69±16.14	943±864	9750±1317	42.07±16.74	6.82±0.23
RCS 15-30	14.83±7.45	17.97±14.51	587±375	9661±1281	11.65±1.39	6.87±0.19
Spmf 0-15	13.57±2.14	7.80±0.65	471±225	11929±2893	38.33±9.31	6.91±0.21
Spmf 15-30	17.33±2.19	5.91±1.04	402±250	12240±2730	20.84±9.95	6.89±0.21
ANOVA F	0.47	0.90	0.79	2.00	2.19	0.51
P	0.794^{ns}	0.512^{ns}	0.580^{ns}	0.150^{ns}	0.124^{ns}	0.765^{ns}

7.3.2 Chemical properties of the soil

Soil pH ranged from 5.5 to 7.3 with a mean value of 6.8 in the 0-15 cm depth and 5.7 to 7.75 with a mean value of 6.87 in the 15-30 cm depth (Table 6.2). These values are considered as fairly neutral and allow nutrients such as N, P, K, Ca and Mg to be

available in the soil. pH is particularly important for P availability which is strongly influenced by pH. For N it is less important for N availability but for the soil microbial activity which plays a basic function in the decomposition processes.

Total N values ranged from 7.4 to 48.23 units with a mean value of 19.9. The largest values were recorded in the 15-30 cm (3.7 to 51.9), depth and are the result of the N leaching during the rainy season. Similar patterns were shown by the S.O.M. %, which ranged from 7.4 to 63.2 and from 7.26 to 46.75 at 0-15 and 15-30 cm depth respectively, the main values for these depths were 22.33 and 17.46 (Table 6.2). The major increment of S.O.M. was recorded at the 0-15 cm after the rain season and a small decrease at 15-30 cm which indicates the transformation of S.O.M. to other forms through the decomposition or as source of energy for microorganisms and insects.

The P concentrations ranged from 0.30 to 95.6 units at 0-15 cm depth with a mean value of 16.4 and from 0.18 to 72.2 at the 15 -30 cm depth with a mean value of 10.25. The highest values were recorded at 0-15 cm depth (15-30). K and Ca soil concentrations showed a similar pattern over time, for K (0-15 cm) the range values were between 21.35 and 2785, with a mean value of 647.3, and from 208 to 2,544 mg/kg-1 with a mean value of 569.4 in the depth of 15 to 30 cm. Ca soil concentrations were similar at both sampling depths (0-15 and 15-30 cm), with ranges from 2,514 to 24,440 and from 2,440 to 20,154, with mean values of 9,637 and 9,260 respectively (Table 7.2).

Table 7.2 Mean, minimum and maximum values for N, P, K, Ca soil concentrations and pH and S.O.M. % in soil at Sierra de Atoyac, Mexico.

	Depth 0-15 cm	*Depth 15-30 cm*
N (mg/kg)		
Mean	19.9 ± 2.19	21.08 ± 2.00
Min	7.4 ± 3.34	3.7 ± 3.05
Max	48.23 ± 2.19	51.90 ± 2.0
P (mg/kg)		
Mean	16.4 ± 3.84	10.25 ± 2.53
Min	0.30 ± 5.86	0.18 ± 3.86
Max	95.6 ± 3.84	72.2 ± 2.53
K (mg/kg)		
Mean	647.3 ± 137	569.4 ± 105
Min	21.35 ± 209	208 ± 160
Max	2,784 ± 137	2,544 ± 105
Ca (mg/kg)		
Mean	9,637 ± 944	9,260 ± 615
Min	2,514 ± 1441	2,440 ± 926
Max	25,554 ± 944	20,154 ± 615
pH		
Mean	6.8 ± 0.09	6.87 ± 0.09
Min	5.5 ± 0.13	5.7 ± 0.14
Max	7.3 ± 0.09	7.75 ± 0.09
S.O.M. (%)		
Mean	22.33 ± 3.1	17.46 ± 3.55
Min	7.4 ± 4.73	7.26 ± 2.32
Max	63.2 ± 3.1	49.75 ± 3.55

Note: n=21 samples per site. Total n=63. Mean values (±SE), Tukey test ($p \leq 0.05$).

7.3.3 Soil chemical changes over time

A one way between groups analysis of variance was conducted to observe the differences of soil nutrient concentrations. Three groups of systems belonging to TCS, RCS and Spmf and two sampling depths (at 0-15 and 15 – 30 cm depth) were analyzed. There was a statistically significant difference at the $p \leq 0.001$ levels between systems for P (Annex Table 7.1.) and Ca (Annex Table 7.2.) at both depths and for K just at the 15-30 cm depth (Annex Table 7.2). There were significant differences at sampling intervals in P (0-15 cm) and Ca (15-30cm). N soil concentration ANOVA values don't differ significantly between systems but did in sampling dates at both depths (Annex Table 7.1).

The S.O.M. % differed significantly between systems and in sampling dates at depths of 0-15 cm and pH didn't show any significant differences in any of the sources of variation analysed (Annex Table 7.3).

Regression analyses were performed for each of the parameters analysed against time and the following graphics were obtained:

7.3.3.1 Soil N concentrations over time (0-15 and 15-30 cm depth)

N concentration at the 0-15 cm of depth (R^2= 0.1938), show a decrease in the values over the first 6 sampling dates with a constant decrement over time (Table 7.7) but an increment in N concentration was registered for the 15-30cm depth soil samples (R^2= 0.7611 for each system) which curves which describe an initial decrement in values and after the 6th sampling date an increment in N soil concentrations about 75 % from the initial values recorded. Similar behaviour in N soil concentrations were observed in the three systems (Fig. 71).

Table 7.3 Polynomial regression equations to describe variations in soil nitrogen (N) over time in TCS, RCS and Spmf.

System	Regression equation	R^2
TCS (0-15 cm)	$y = 0.0001x^2 - 0.0514x + 21.083$	0.2188
RCS (0-15 cm)	$y = 8E\text{-}05\ x^2 - 0.0568x + 22.475$	0.3921
Spmf (0-15 cm)	$y = 0.0001\ x^2 - 0.0483x + 23.78$	0.0618
TCS (15-30 cm)	$y = 0.0005\ x^2 - 0.148x + 23.547$	0.7684
RCS (15-30 cm)	$y = 0.0003\ x^2 - 0.0656x + 21.153$	0.6077
Spmf (15-30 cm)	$y = 0.0004\ x^2 - 0.0698x + 21.475$	0.7164

(a)

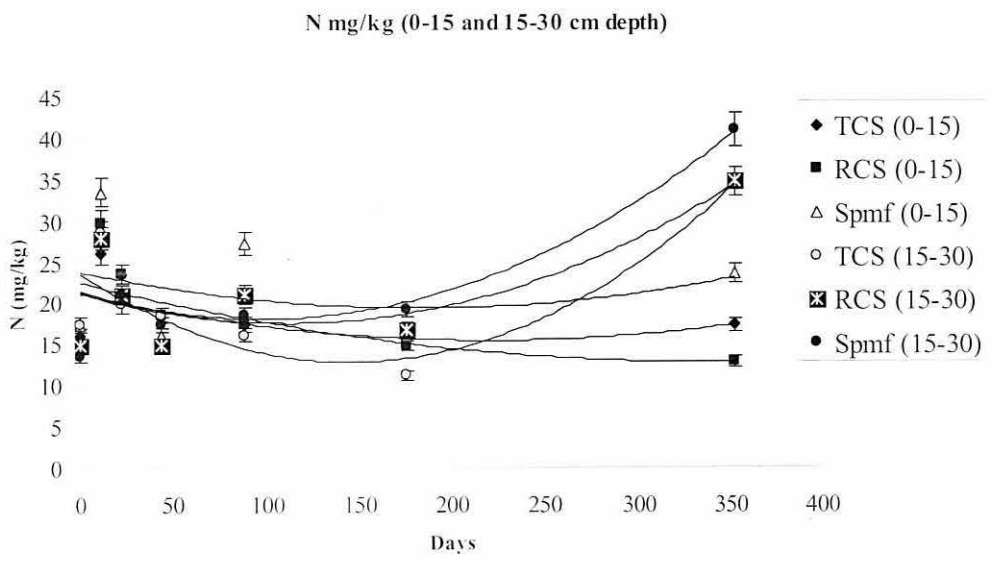


Figure 7.1 Regressions of soil N content over time in TCS, RCS & Spmf in San Miguel, Veracruz. México.

7.3.3.2 Soil P concentrations over time (0-15 and 15-30 cm depth)

Differences in the initial concentrations are shown in Fig. 7.2, in which an increment in soil P concentration, in the order of RCS, SPMF and TCS respectively and a R^2=0.9362 (Table 7.8), explain the variability in soil P. A slight increment followed by a decrement show concentrations almost constant over time in the three systems for 15-30 cm depth samplings (Fig. 7.2) and a R^2=0.7357 for the explaining around the 70% of variability in the P soil concentration (Table 7.8).

Table 7.4 Polynomial regression equations to describe variations in soil phosphorus (P) over time in TCS, RCS and Spmf

System	Regression equation	R^2
TCS (0-15 cm)	$y = 0.0004\ x^2 - 0.0584x + 7.1989$	0.9713
RCS (0-15 cm)	$y = 0.0003\ x^2 - 0.0325x + 13.991$	0.8938
Spmf (0-15 cm)	$y = 0.0003\ x^2 - 0.0085x + 9.0382$	0.9619
TCS (15-30 cm)	$y = 2E\text{-}05\ x^2 - 0.0014x + 6.5305$	0.383
RCS (15-30 cm)	$y = -3E\text{-}05\ x^2 + 0.0022x + 13.369$	0.1883
Spmf (15-30 cm)	$y = -0.0001\ x^2 + 0.05x + 6.5675$	0.7994

(b)

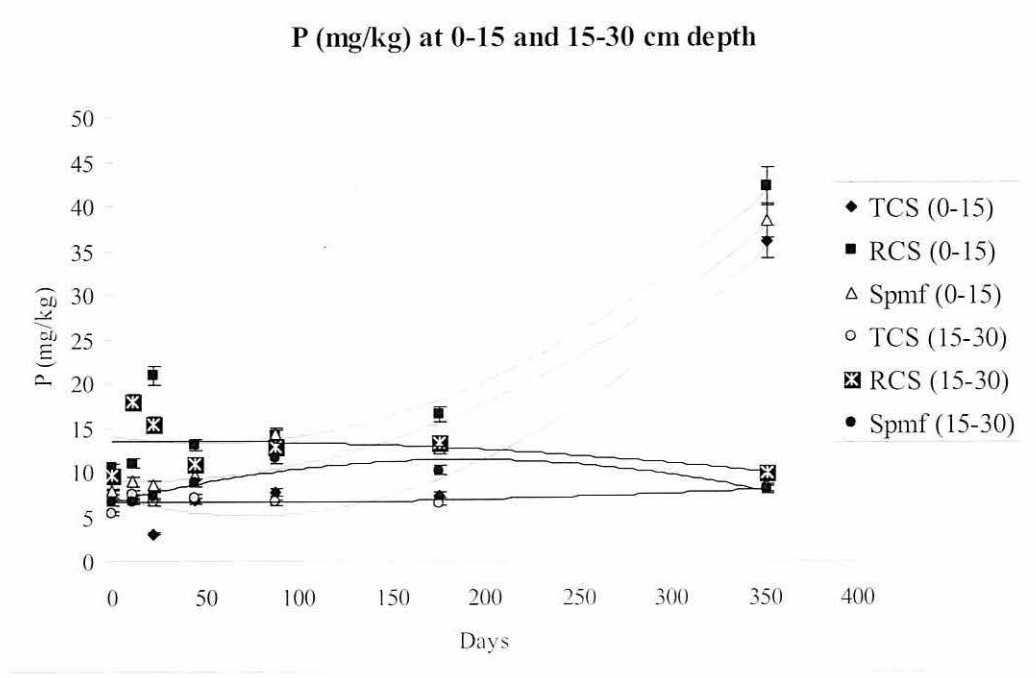


Figure 7.2 Regressions of soil P content over time in TCS, RCS & Spmf in San Miguel, Veracruz. México.

7.3.3.3 Soil K concentrations over time (0-15 and 15-30 cm depth)

Constant and low values for K at both soil depths (0-15 and 15-30 cm) were observed during the sampling (Fig. 7.3) and with R^2 values of 0.1938 and 0.7611 respectively that explain the variability at both depths (Table 7.9), show a low level of soil K in a vertisol, which are not rare on this type of soil in the tropics

Table 7.5 Polynomial regression equations to describe variations in soil potassium (K) over time in TCS, RCS and Spmf

System	Regression equation	R^2
TCS (0-15 cm)	$y = 2E\text{-}05\ x^2 + 0.1447x + 408.72$	0.0743
RCS (0-15 cm)	$y = -0.0192\ x^2 + 7.3822x + 558.15$	0.6413
Spmf (0-15 cm)	$y = -0.0014\ x^2 + 1.2336x + 509.65$	0.6062
TCS (15-30 cm)	$y = 0.0005x^2 - 0.0957x + 344.96$	0.2283
RCS (15-30 cm)	$y = -0.0095x^2 + 3.4898x + 728.46$	0.5769
Spmf (15-30 cm)	$y = -0.008\ x^2 + 3.1115x + 388.85$	0.9509

(c)

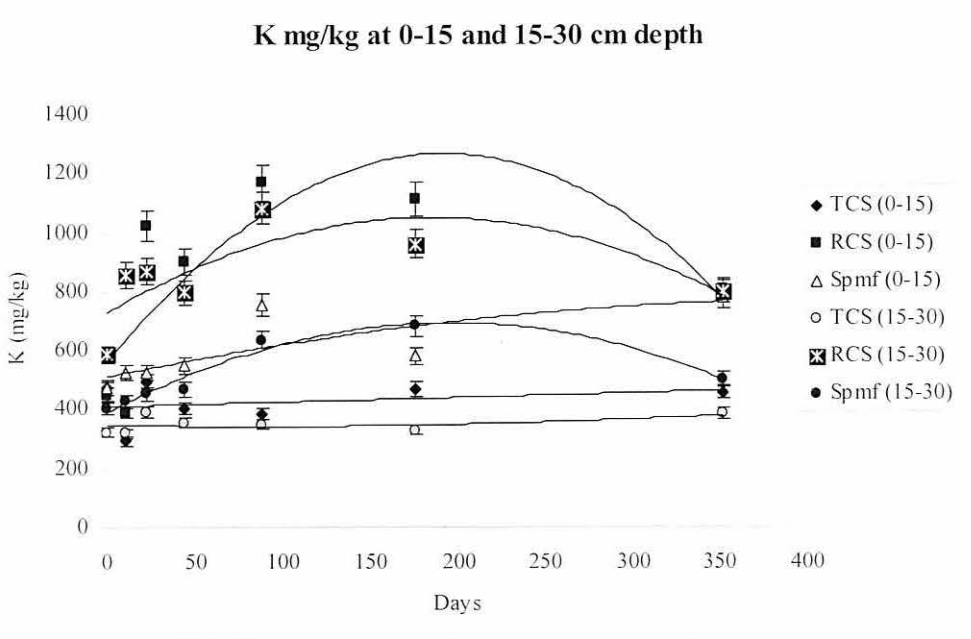


Figure 7.3 Regressions of soil K content over time in TCS, RCS & Spmf in San Miguel, Veracruz. México.

7.3.3.4 Soil Ca concentrations over time (0-15 and 15-30 cm depth)

High Ca concentration at both depths (0-15 and 15-30cm) are reported in the soil analyses performed in the three systems. These values remained almost constant over time (Fig.7.4), and the regression curves explained 19% and 76% of the variability in Ca soil concentration at 0-15 and 15 to 30 cm depth respectively (Table 7.10).

Table 7.6 Polynomial regression equations to describe variations in soil calcium over time in TCS, RCS and Spmf

System	Regression equation	R^2
TCS (0-15 cm)	$y = 0.039 x^2 - 15.584x + 9492.1$	0.1418
RCS (0-15 cm)	$y = 0.0018 x^2 + 3.805x + 8138.7$	0.2947
Spmf (0-15 cm)	$y = 0.0381 x^2 - 10.542x + 10769$	0.0871
TCS (15-30 cm)	$y = 0.0453 x^2 - 13.657x + 8964.5$	0.1709
RCS (15-30 cm)	$y = 0.003 x^2 + 4.2535x + 7665.9$	0.3654
Spmf (15-30 cm)	$y = -0.0396 x^2 + 17.2x + 9427.4$	0.3926

(d)

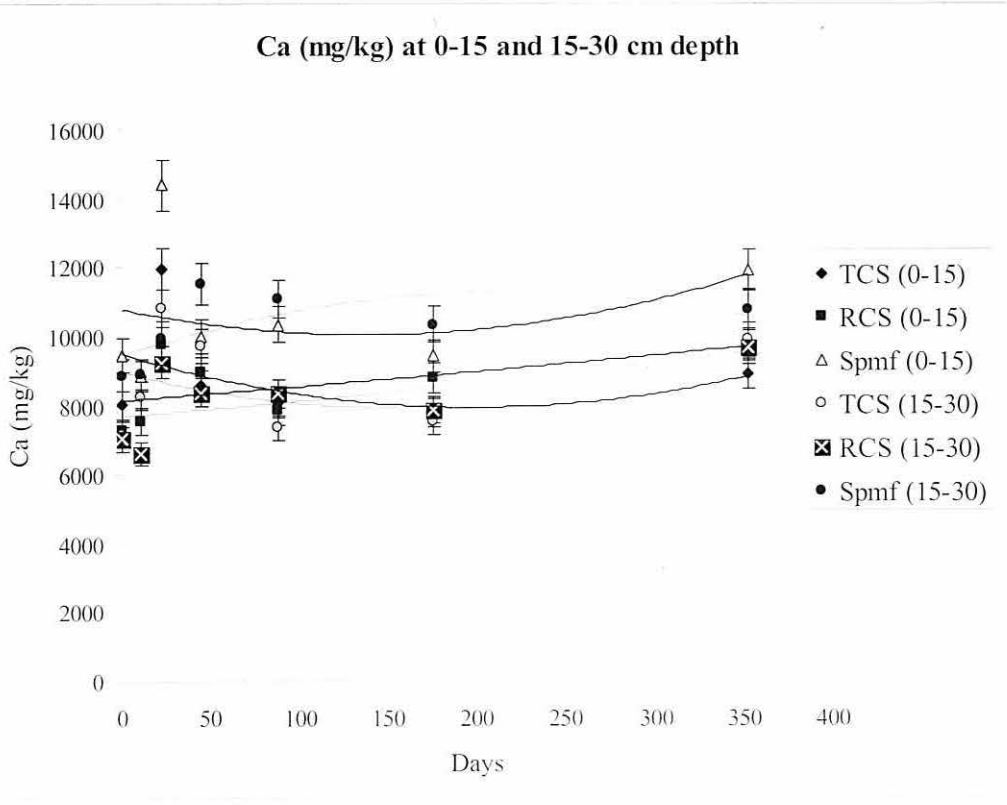


Figure 7.4 Regressions of soil calcium (Ca) content over time in TCS, RCS & Spmf in San Miguel, Veracruz. México.

7.3.3.5 S.O.M. % over time (0-15 and 15-30 cm depth)

S.O.M. higher percentages values at the 0-15 cm of depth were shown and a R^2= 0.8551 explaining a 85 % of the variability of S.O.M at superficial layers (Table 7.11), show a constant increment over time (Fig. 7.5) but an slight decrement for S.O.M. at 15-30 cm depth was observed (Fig. 7.5), the regression curves for S.O.M. at 15-30 cm depth explain just around the 44% of the variability (Table7.11) for each case, similar behaviour about the S.O.M. was observed.

Table 7.7 Polynomial regression equations to describe variations in Soil Organic Matter (S.O.M.) over time in TCS, RCS and Spmf

System	Regression equation	R^2
TCS (0-15 cm)	$y = 0.0003 x^2 - 0.0443x + 15.421$	0.9052
RCS (0-15 cm)	$y = 0.0004 x^2 - 0.0664x + 15.651$	0.9947
Spmf (0-15 cm)	$y = -9E-05 x^2 + 0.0734x + 22.592$	0.5687
TCS (15-30 cm)	$y = -7E-05 x^2 + 0.0308x + 11.932$	0.2499
RCS (15-30 cm)	$y = -0.0001 x^2 + 0.0484x + 12.358$	0.4518
Spmf (15-30 cm)	$y = -0.0003 x^2 + 0.1002x + 22.577$	0.2507

(e)

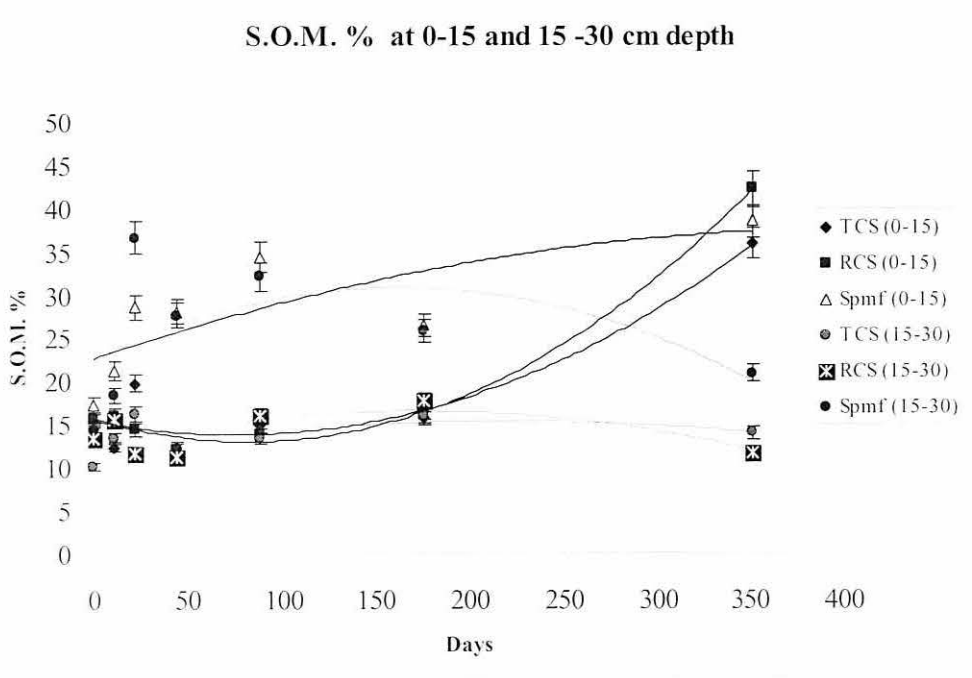


Figure 7.5 Regressions of soil organic matter (S.O.M.) content over time in TCS, RCS & Spmf in San Miguel, Veracruz. México.

7.3.3.6 Soil pH over time (0-15 and 15-30 cm depth)

Soil pH values were constant over the whole year and the slight changes observed over time; don't reflect any possible effect in the soil properties or conditions in any of the systems. Regression analyses were done for pH values during the sampling dates and it were obtained R^2 values of 0.0167 and 0.5029 for 0-15 and 15 to 30 cm depth (Table 7.12), which explain a small percentage of the variability in soil. All the values were inside the range of 6.8 to 7.0 (Fig. 7.6), which corresponds to a neutral soil. Not any significant value was found in the ANOVA for any of the variables

Table 7.8 Polynomial regression equations to describe variations in soil pH over time in TCS, RCS and Spmf

System	Regression equation	R^2
TCS (0-15 cm)	$y = -3E\text{-}06\ x^2 + 0.0014x + 6.7685$	0.2356
RCS (0-15 cm)	$y = -3E\text{-}06\ x^2 + 0.0014x + 6.7228$	0.2871
Spmf (0-15 cm)	$y = 5E\text{-}06\ x^2 - 0.0024x + 6.9623$	0.4405
TCS (15-30 cm)	$y = 2E\text{-}05\ x^2 - 0.0059x + 7.0638$	0.7117
RCS (15-30 cm)	$y = -2E\text{-}06\ x^2 + 0.0008x + 6.8244$	0.0851
Spmf (15-30 cm)	$y = 4E\text{-}06\ x^2 - 0.0013x + 6.8967$	0.1549

(f)

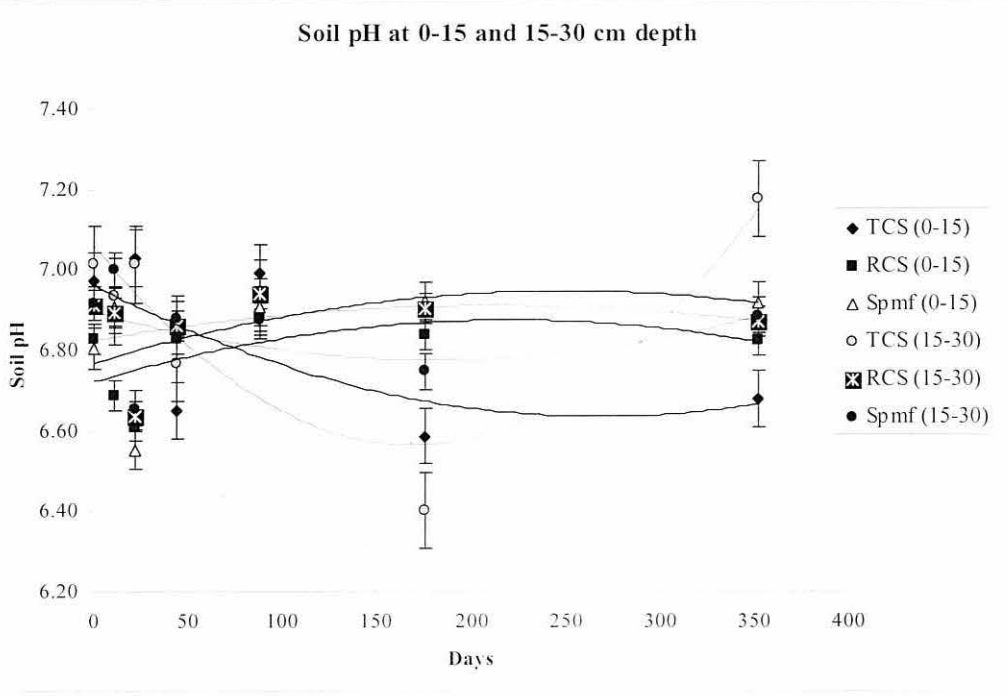


Figure 7.6 Regressions of soil pH content over time in TCS, RCS & Spmf in San Miguel, Veracruz. México.

7.3.4 Correlation analysis results

The relationship was perceived as a positive correlation between N concentration in soil (15-30 cm) and S.O.M. % (0-15 cm), as well as other strong positive correlations were: P (15-30 cm) with K (0-15 cm) and (15-30 cm), K (0-15 cm) with K (15-30 cm), Ca (0-15 cm) with Ca (15-30 cm) and S.O.M. % (15-30 cm) and Ca (15-30 cm) with S.O.M. % at both depths (Table 7.13).

Table 7.9. Pearson N, P, K, Ca, pH and S.O.M. % Correlation in TCS, RCS and Spmf in San Miguel, Veracruz. Mexico.

	N 0-15	*N 15-30*	*P 0-15*	*P 15-30*	*K 0-15*	*K 15-30*	*Ca 0-15*	*Ca 15-30*	*S.O.M. 0-15*	*S.O.M. 15-30*	*pH 0-15*	*pH 15-30*
N 0-15	1											
N 15-30	0.38	1										
P 0-15	-0.41	0.46	1									
P 15-30	-0.26	-0.23	0.58	1								
K 0-15	-0.44	-0.32	0.53	**0.83*** **	1							
K 15-30	-0.06	-0.12	0.51	**0.92*** **	**0.81*** **	1						
Ca 0-15	0.19	0.20	-0.21	-0.48	-0.14	-0.16	1					
Ca 15-30	0.07	0.31	0.00	-0.40	-0.13	-0.09	**0.92*** **	1				
O.M. 0-15	0.16	**0.75*** **	0.42	-0.28	-0.18	-0.05	0.63	**0.79*** **	1			
O.M. 15-30	0.33	0.03	-0.26	-0.29	-0.20	-0.01	**0.75*** **	**0.81*** **	0.57	1		
pH 0-15	0.09	-0.02	-0.20	-0.24	-0.14	-0.26	-0.14	0.02	0.00	0.12	1	
pH 15-30	0.21	0.55	0.16	-0.22	-0.12	-0.25	-0.22	-0.18	0.14	-0.41	0.54	1

Note: N=Nitrogen, P=Phosphorus, K=Potassium, Ca=Calcium, O.M.=Organic matter in percentage, and pH.

Numbers in bold represent significant correlation values (***$p \leq 0.001$)

The results show the strong relationship between P and K and Ca respecting to O.M. % in soil. A strong relationship between N and O.M. % was perceived as well in the correlations results.

7.4 Discussion

Total N, P and K concentrations were generally very low in the three systems and depths, as is usual for Vertisol soils in the Gulf of Mexico region (Castellanos et al., 2000), The increase levels of Total N depth is as expected because of leaching by rain and the increase levels of P at the surface also was expected low, due to fixation by organic matter, and because of the low mobility of this element. Ca instead showed very high initial values which remained constant all over the sampling dates; this is due to the karstic origin of the soil mainly. Organic matter seems to have effect for the rise in N and P concentrations, but as expected, remain constant at lower depths in the soil, which are already in other organic forms and forming part of the mineral soil.

The values observed for soil pH ranged from 6.65 to 7.0 and are considered neutral (Havlin et al., 1990), probably influenced by the karstic origin of the soil and remained more or less constant over the year. N, P, and K values are reported within the normal range for a Vertisol in Mexico.

Soil Nitrogen (N)

Soil N values were between 20 and 30 mg/kg^{-1} and considered as low for a Vertisol (Castellanos et al., 2000). The regression model developed for the depth of 0-15 cm shows a slight but constant decreasing during the sampling period, with a loss between 20 and 25 % from the initial values. This can be indicative of immobilization of mineral N by factors such as the growth of decomposer micro-organisms and the action of the physical-chemical conditions of temperature, humidity and pH that are optimal for the immobilization process. However, this was largely due to the effect of leaching over the N availability in the superficial strata during the rain season (end of May to October). The mineral N is leached as NO_3 to lower soil strata thus contributing to the concentration of N in lower soil depths. With an increase close to 75 % from the initial N concentration values for the three systems at the 15-30 cm, is an important effect for soil nutrient availability. In general, the N soil conditions in the TCS, RCS and Spmf are ideal for the growth of the coffee plants. In general, the N soil conditions in the TCS, RCS and Spmf are ideal for the growth of coffee (Dominguez, 1999).

Soil phosphorus (P)

After nitrogen, phosphorus is the second most important nutrient plant because of its low availability which depends on the soil pH and other mineral compounds. It is a very immobile nutrient especially in the presence of water or warm temperatures, higher concentrations in warmer climates than in cold soils. For fixation the physical and chemical adsorption, the anionic exchange and the superficial precipitation are important elements (Aguilar and Heil, 1988).

P fixation can occur on Mn and Al hydroxides when pH is below seven, but above it, it will be as Ca phosphates. The highest P availability occurs when the pH is between 6.0 and 6.5 but is only slightly less in pH from 6.5 to 7.0.

Data for P levels in vertisols in México entirely corresponds to those of this experiment in Sierra de Atoyac, Veracruz, México (Alvarez-Sánchez, 1995; Alvarez-Sánchez and Becerra, 1996). The values obtained for the P concentrations at soil depth 0-15 cm in the TCS and Spmf were very low initially (between 5 and 7 mg/kg^{-1}) although the release curve shows an increment during the last sampling dates up to 34 mg/kg^{-1}, which is moderately high. For RCS at the same depth, the initial values were close to 18 mg/kg^{-1} and are considered as "moderately low" up to 48 mg/kg^{-1}. This increase P levels in the superficial soil can be directly linked to the solubility of P when conditions such as soil humidity, clay textures, warm temperatures and organic matter in the site are optimal (Borie and Zunino, 1983).

Clay particles tend to retain or fix phosphorus in soils. Consequently, fine-textured soils such as clay loam soils have a greater phosphorus fixing capacity than sandy coarse-textured soils. Clays of the 1:1 type (kaolinite) have a greater phosphorus fixing capacity than the 2:1 type clays (montmorillonite, Illite, vermiculite). Soils formed under high rainfall and high temperatures contain large amounts of kaolinitic clays and therefore have a much greater fixing capacity for phosphorus than soils containing the 2:1 type clay. High temperatures and high rainfall also increase the amount of iron and aluminum oxides in the soil which contributes greatly to the fixation of phosphorus added to these soils that may happen in the oils sampled in San Miguel (Havlin et al., 1999).

Soil Potassium (K)

Potassium (K) in tropical soils exists only in very low concentrations, usuallyless than 125 mg/kg^{-1}, and is not a limiting element for plant growth. A typical K level in some regions in Mexico is about 8 to 25 mg/kg^{-1} (Castellanos *et al.*, 2000a).

The analysis for the 0-15 cm depth in the TCS is considered as "very low" (65 mg/kg^{-1}), whereas the Spmf showed "low" rank" concentrations (140 mg/kg^{-1}). The change in concentration of K throughout sampling period remains constant. A similar situation happens with the TCS and Spmf for the depth of 15-30 cm, where the values are between 120 and 140 mg/kg^{-1} considered as "low" and remain constant over the year. However for the RCS in both depths, the K concentrations were higher than the other systems and are within "medium" concentration levels of 230 mg/kg^{-1} at a depth of 0-15 cm and 200 mg/kg^{-1} for depth 15-30 (Castellanos et al, 2000), probably because of the litter quality of these sites.

Soil Ca

Ca is mainly transferred to the soil via litterfall, because of their strong link to leaf structure. Some factors that can affect the availability of Ca in soil are: soil pH; cation exchange capacity, clay type, the relationship of Ca with other cations and water in the soil but usually this divalent cation moves slower than the other monovalent cations into the ecosystem. The TCS and RCS systems had Ca soil concentration values between 7,500 to 9,000 mg/kg^{-1} and Spmf between 10,500 and 12,000 mg/kg^{-1} (Fig. 7.4), all considered as very high (Etchevers et al., 1971; Castellanos et al., 2000), and remained constant throughout the year, indicating that it is due to the Karstic origin of the soil and the litterfall production.

Soil Organic Matter (S.O.M.)

S.O.M. comprises organic materials in all stages of decomposition and is composed of relatively stable material termed as humus, which is resistant to further rapid decomposition. Organic materials that are subject to fairly rapid decomposition range from fresh crop residues to relatively stable amount of humus in soil. The primary microbial processes involved in the fresh residue and humus turnover or cycling in soils are mineralization and immobilization. These reactions combined with other

factors such as climate, physical-chemical soil characteristics and the effect of leaching are important for the soil organic matter stability and the inorganic N and P availability in soils (Etchevers et al., 1997). The S.O.M. content in soil can retain moisture, protect against extreme temperatures (Schroth and Sinclair, 2003) and it is also the substrate for soil biota and can be a very important factor in the growth of insect, bacteria and fungus colonies as well for the control of populations of plant pathogens in the soil, by stimulating the activity of antagonistic micro-organisms (Magdoff and Weil, 2004) or in other case it can immobilized nutrients for long periods .

The initial high S.O.M. percentages for the three systems at 0-15 cm depth ranged around 22.33 and at the 15-30 cm depth were 17.46. Similar values have been recorded for Vertisols in Cuba for tropical forests and are considered as rich soils in S.O.M (Sanchez-Vera et al., 2003) and can be common in tropical forests soils. The percentages of S.O.M. at a depth of 0-15 cm in the three systems showed a slight increase, but after the start of the rainy season there was a steep rise in values of about 50 % from the initial values in Spmf and more than 100% in TCS and RCS, probably this is a direct effect from decomposition of leaf litter in this systems.

The increase in S.O.M. content could be influenced by the other environmental factors such as the increase in the humidity and temperature which also affect the growth of colonies of micro-organisms and insects that control the processes of decomposition of the leaf litter (Immobilization) and their consequent incorporation to the soil but that not always means a higher availability of the soil nutrients for the plants. Organic matter can also have influenced the increase in P for the three systems in the 0-15 layer, as it is complexed in the superficial horizons.

At a soil depth of 15-30 cm, the values were virtually constant throughout the whole year. The highest values of S.O.M. content were recorded in the Spmf at the two depths, approximately between 30% and 50 %. In the coffee systems the S.O.M. percentages were lower (Fig. 7.5). The regression values of R^2 of 0.8551 and 0.4445 for Spmf and TCS and RCS respectively explain 85 % and 44% of the S.O.M. variability in these systems (Table 7.11).

The organic matter is probably the most important factor for the regulation of the litter decomposition processes in the systems, which will be decomposed over time and so the basic cations will be leached through the rain. The soils with a high content of organic matter tend to have a higher electric conductivity, higher porosity, and less soil compaction, all these conditions represent better conditions for growth and nutrition of plants. S.O.M. is also linked to the availability of Fe, Mn, Cu and Zn. It is a source of humic and fulvic acids which take part in the physical-chemical soil processes as well in the physiology of the plants. Also the Karstic origin of the soil influences the possible P fixation as calcium phosphates (Jordan, 1985).

7.5 Conclusions

The Vertisols analysed in the municipality of San Miguel Veracruz, did not differ much from other soil studies in Mexico and Cuba (Sanchez-Vera et al., 2003). Soil organic matter (S.O.M.) is one of the most important components for the re-cycling of nutrients and sustainability of tropical forests, agro-ecosystems and disturbed ecosystems, providing additional recycling and exchange sites for cations, nutrient availability and maintenance, sequestration of C and erosion prevention, thereby decreasing leaching potential. N is bound in the S.O.M. and it is released in synchrony with the plant demands than it would be as nitrates or ammonia, which are the common forms of inorganic nitrogen in mineral soil (Brady and Weil, 2002) Nevertheless in the soils analyzed seems that the strong effect produced by the rain leaching on the soil nutrients as N and Ca have a strong effect in the pH and N availability of these systems. S.O.M. can make the soil less susceptible to erosion and is the source of energy for micro-organisms whose activities render the soil more permeable to roots (Jordan III, 1988).

N, P and K showed in general very low to medium concentrations at the three systems and depths, as is usual for Vertisolic soils in the Gulf of Mexico region (Castellanos et al., 2000; Chávez et al., 2003), The increase in N concentration with depth as a consequence of leaching by the rain and the retention of P in the superficial soil layers was also expected due to the direct relationship with S.O.M. and organic matter production. Ca showed very high initial values which remained constant throughout

the sampling period. This is due to the karstic origin of the soil and probably to the litter production in the systems.

The pH was expected to be more basic because of the high quantity of cations as Ca and Mg present in the karstic soil origin, but probably because a high effect of leaching (through the rain season) and high organic matter production it tended to be lower or around 7.0. The neutral soil pH contributes to the mobility and mineralization of the nutrients on the systems as well a probable reduction of the toxic elements, Al and Mg. In general the soil seems to provide optimal conditions for growth of plants and trees in the systems.

8 Discussion

8.1 Aim of thesis

The broad aim of this thesis was to investigate factors that control the rate of decomposition of leaf litter in agroecosystems with different forest canopy species composition and variable rates of litter production. In traditional (TCS), rustic coffee systems (RCS) and disturbed native forest (Spmf). I studied the tree canopy species composition and measured input mass loss and "k" values (Chapter 4), and the litter qualities and decomposition rates (Chapters 5 and 6) and soil chemistry over a period of (Chapter 7) during seven sampling dates over 352 days. In addition, to gain a better understanding of the fundamental processes of decomposition, I studied how the rate and pattern of loss of mass from leaf litter is affected by its initial chemical composition (Chapter 7) and asked the question; is decomposition mainly driven by litter quality, soil chemistry or climate features.

8.2 Summary of experiments

A total of 82 tree canopy species were recorded and of these the Fabaceae was the most representative botanical family (13 species), 15 species in the TCS, 62 in RCS and 66 in Spmf. Canopy species richness in forest plots was similar to the RCS, but of different species composition and different dominant species. Litter diversity can affect amongst other things, plant establishment, growth and community development (Gartner and Cardon, 2004; Hättenschwiler and Gasser, 2005).

For this study I choose to investigate the effect of different mixes of litter representing the general vegetation of the zone which included a representative species of the zone (*Robinsonella mirandae*), plus coffee; a representative species for each of the systems (*Mastichodendron capiri, Piper hispidum* and *Croton officinalis*), and finally a mixture of the species of each system and the coffee (Chapter 5).

Results showed that litter rates of decomposition and nutrient cycling are correlated with the chemical properties of the litter. This includes N concentration, C:N and lignin:N ratios. Tree species growing in nutrient-poor environments tend to produce

low quality litter with a slower decomposition process than those in a rich environment where the trees will produce a better quality litter (Carreiro et al., 1999, 2000).

The litter produced in the plots studied was mainly considered to be of medium quality, but three of the mixes were reported as high quality (*Robinsonella mirandae/Coffea arabica* in RCS, *Mastichodendron capirii* and *Piper hispidum*) and one as poor quality (*Croton officianlis*).

Litter quality had a large effect on the rate of loss of mass from litterbags. Of the four mixes compared, the litter tested in RCS had a faster decomposition rates than the rest of the leaf litter. During the experiment the litter mixes decomposed in the following order: *Piper hispidum* (RCS) > Mix litter (RCS) > *Robinsonella mirandae/Coffea arabica* (RCS) > *Robinsonella mirandae* (all systems) > *Robinsonella mirandae/Coffea arabica* (TCS and Spmf) > Mix litter (TCS, Spmf) > *Mastichodendron capirii* > *Croton officinalis* and *Piper hispidum* which showed the biggest loss of mass at the end of the experiment (0.7 % of mass remaining and highest k values 5.19), during the 352 d incubation (Table 7.1).

The initial content of soluble compounds of N and P in the litters best predicted their rates of decomposition, which is consistent with results from other studies (Goh and Totua 2004; Loranger et al., 2002; Nyberg et al., 2002) but still does not explain the magnitude of the differences between the species. The Lignin:N and C:N ratios were the parameters which best explained the variability in the litter tested and were used in regressions against "k" values of the litter. C:N and Lignin:N ratios were constant across all experiments although it may have varied unpredictably between the coffee systems and Spmf during the decomposition process (Blair et al., 1990; Didham, 1998) because of soil nutrient mobilization and varying plant species composition (Rankin-de-Merona et al., 1992).

I investigated whether the rates of decomposition of leaf litter in coffee systems (TCS and RCS) were greater than those of the native forest (Spmf). In this case, the k values were similar in the Forest and the TCS, but varied in the RCS, mostly for the litter mixtures and the representative species *Piper hispidum* (RCS) which registered the

highest k values for all the litters. Most studies of decomposition indicate that high quality litter in mixtures can have an important effect on decomposition rates and probably influences the rest of the litter in the system.

Table 8.1 ***Summary of main treatment effects.*** **Characteristics and effects of litter quality (Lignin: N and C:N ratios) on the initial (0 to 176 d), later (176 to 352 d) and overall (0 to 352 d) loss of mass and "k" rates values, from litterbags in TCS, RCS and Spmf**

Litterbag mixes	Treatment	Litter quality	Mass remaining (days) *0-176*	*176-352*	"k" values (days) *0-176*	*176-352*	*Parameter* R^2		Overall *0 to 352 d*
Robinsonella mirandae	TCS	Medium	31.3 %	17.0 %	-2.40	-1.85	N	83.3	All litterbags registered similar patterns in increased mass loss during the first phase of decomposition and "k" values (0-176 d.) and values decreased during the second stage (176–352 d). The highest values for "k" at the 22nd d, which subsequently decreased as did mass loss. The highest mass loss was recorded for *Piper hispidum* and *Robinsonella mirandae* but for all the litter tested in RCS an important decrease in mass remaining was observed. *Croton officinalis* showed the smallest "k" value and highest mass remaining during the first part of the decomposition process and a slow decomposition after 176 d of experiment. The chemical parameters that best explained the variability in decomposition over time, apart from lignin: N and C:N were: N , P and cellulose for litter of high and medium quality and lignin for the low quality litter (*Croton officinalis*).
	RCS	Medium	33.3 %	14.0 %	-2.25	-2.03	N	66.3	
	Spmf	Medium	33.3 %	14.0 %	-2.28	-2.03	Cel	80.3	
Robinsonella mirandae/Coffea arabica	TCS	Medium	46.7 %	43.3 %	-2.08	-1.09	P	82.3	
	RCS	High	43.3 %	12.7 %	-1.73	-2.14	N	72.9	
	Spmf	Medium	38.7 %	33.3 %	-1.97	-1.14	N	88.8	
Mix litter	TCS	Medium	43.3 %	34.7 %	-1.73	-1.09	P	74.3	
	RCS	Medium	48.7 %	8.0 %	-1.49	-2.62	Cel	72.2	
	Spmf	Medium	52.0 %	39.3 %	-1.36	-0.97	Ca	52.9	
Representative species per System	*Mastichodendron capirii*	High	46.7 %	44.7 %	-1.58	-0.83	N/Cel	58.8	
	Piper hispidum	High	44.0 %	0.7 %	-1.70	-5.19	Cel/Lig	72.6	
	Croton officinalis	Low	50.7 %	30.7 %	-1.41	-0.33	Lignin	90.4	

8.3 Final conclusions, key contributions, recommendations and areas for further studies

In conclusion, six key findings of this thesis were:

1) Changes in the structure and species composition in the tree canopy led to changes in litter production in coffee systems. These changes affected the litter standing crop as well the quality of the leaf litter deposited on the coffee plantation floor, specifically in the rustic coffee systems (RCS)

2) Litter quality parameters are a fundamental tool to determining the rates of leaf litter decomposition in agro-ecosystems. The parameter that best explained the variability of overall decomposition was lignin:N ratio, but initial N, P and hemicelluloses can explain a good proportion of variability of the decomposition process as well.

3) Differences in quality of the litter mixes studied were found to determine rates of decomposition and recycling of leaf litter, probably affecting the decomposition of mixed floor litter. Initial litter content of N, P, K, Ca, correlated positively with k values of tree leaf litter during the first part of the decomposition process and cellulose, hemicelluloses and lignin negatively with the second part of the process from 176 to 352 d., C:N and lignin:N ratios showed an initial increase related to rates of decomposition but then slowed down during the second stage of decomposition.

4) Soil nutrient dynamics did not have any important effect on the decomposition rates of litter but a positive correlation between litter N, P and S.O.M. show the importance of the litter in nutrient contribution to the soil.

5) The differences between the initial (0-176 d) and later stages of decomposition (176-352 d) support the hypothesis of the existence of two different phases of the decomposition process, probably influenced by

climate (dry and wet seasons); the quality of litter; and the soil decomposing micro-organisms.

6) Nutrients were more rapidly released from litterfall of higher quality and could also stimulate the "decay" of the rest of the litter present. Alternatively, the decomposition of litter could be restricted by the liberation of inhibiting compounds such as phenols and tannins (Salamanca et al., 1998)

It is recommended that further studies of micro-organism diversity, succession and the role that they play in tropical ecosystems be studied, as well as other agroforestry systems with some complementarily in the composition of tree canopies to forests, in order to better understand the processes of decomposition and how they are affected by disturbance.

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ANNEXES

Annex 1:Localization of experimental plots. San Miguel, Veracruz. México.

Plot 1: TCS Subplot: 1: N: 18°56.339′ W: 096°50.511′ h: 756 m.	Plot 1: TCS Subplot: 2 N: 18°56.337′ W: 096°50.520′ h: 759 m.	Plot 1: TCS Subplot: 3 N: 18°56.332′ W: 096°50.519′ h: 751 m.
Plot 2: TCS Subplot: 1 N: 18°56.014′ W: 096°50.540′ h: 728 m.	Plot 2: TCS Subplot: 2 N: 18°56.323′ W: 096°50.541′ h: 724 m.	Plot 2: TCS Subplot:3 N: 18°56.326′ W: 096°50.558′ h: 711 m.
Plot 3: TCS Subplot: 1 N: 18°56.319′ W: 096°50.557′ h: 709 m.	Plot 3: TCS Subplot: 2 N: 18°56.341′ W: 096°50.560′ h: 728 m.	Plot 3: TCS Subplot: 3 N: 18°56.344′ W: 096°50.560′ h: 743 m.
Plot 1: RCS Subplot: 1 N: 18°56.347′ W: 096°50.563′ h: 744 m.	Plot 1: RCS Subplot: 2 N: 18°56.300′ W: 096°50.477′ h: 769 m.	Plot 1: RCS Subplot: 3 N: 18°56.297′ W: 096°50.482′ h: 781 m.
Plot 2: RCS Subplot: 1 N: 18°56.288′ W: 096°50.469′ h: 785 m.	Plot 2: RCS Subplot: 2 N: 18°56.287′ W: 096°50.463′ h: 789 m.	Plot 2: RCS Subplot: 3 N: 18°56.280′ W: 096°50.462′ h: 792 m.
Plot 3: RCS Subplot: 1 N: 18°56.282′ W: 096°50.459′ h: 795 m.	Plot 3: RCS Subplot: 2 N: 18°56.288′ W: 096°50.455′ h: 758 m.	Plot 3: RCS Subplot: 3 N: 18°56.297′ W: 096°50.464′ h: 780 m.
Plot 1: Spmf Subplot: 1 N: 18°56.275′ W: 096°50.449′ h: 808 m.	Plot 1: Spmf Subplot: 2 N: 18°56.274′ W: 096°50.432′ h: 808 m.	Plot 1: Spmf Subplot: 3 N: 18°56.272′ W: 096°50.430′ h: 815 m.
Plot 2: Spmf Subplot: 1 N: 18°56.266′	Plot 2: Spmf Subplot: 2 N: 18°56.269′	Plot 2: Spmf Subplot: 3 N: 18°56.267′

W: 096°50.428′ h: 819 m.	W: 096°50.436′ h: 814 m.	W: 096°50.447′ h: 802 m.
Plot 3: Spmf Subplot: 1 N: 18°56.277′ W: 096°52.444′ h: 819 m.	Plot 3: Spmf Subplot: 2 N: 18°56.272′ W: 096°51.439′ h: 814 m.	Plot 3: Spmf Subplot: 3 N: 18°56.278′ W: 096°51.433′ h: 832 m.

Table 6.1 Results of Two-way ANOVA on variations in the N content of leaf litter samples with respect to time and system

Source of variance	Degrees of Freedom	Sums of Squares	Mean Square	F	P
Within Samples	2	0.0383	0.0191	2.02	0.136^{ns}
Between litter/Systems	11	0.3003	0.0273	2.88	0.002**
Between Times	6	1.2056	0.2009	21.17	0.000***
Time * System interaction	66	2.0872	0.0316	3.33	0.000***
Error	166	1.5758	0.0094		
Total	251				
Levene's test for homogeneity of variance					0.684^{ns}

Table 6.2 Results of Two-way ANOVA on variations in the P content of leaf litter samples with respect to time and system

Source of variance	Degrees of Freedom	Sums of Squares	Mean Square	F	P
Within Samples	2	0.0007	0.0035	1.78	0.172ns
Between Systems	11	0.0075	0.0006	3.52	0.000***
Between Times	6	0.0347	0.0057	29.66	0.000***
Time * System interaction	66	0.0407	0.0006	3.16	0.000***
Error	166	0.0324	0.0002		
Total	251				
Levene's test for homogeneity of variance					0.903^{ns}

Table 6.3 Results of Two-way ANOVA on variations in the K content of leaf litter samples with respect to time and system

Source of variance	Degrees of Freedom	Sums of Squares	Mean Square	F	P
Within Samples	2	0.0005	0.0027	0.05	0.948ns
Between Systems	11	0.3243	0.0295	5.81	0.000***
Between Times	6	1.9702	0.3285	64.69	0.000***
Time * System interaction	66	1.2721	0.0193	3.80	0.000***
Error	166	0.8429	0.0050		

Total	251				
Levene's test for homogeneity of variance					0.456^{ns}

Table 6.4 Results of Two-way ANOVA on variations in the Ca content of leaf litter samples with respect to time and litter type/system

Source of variance	Degrees of Freedom	Sums of Squares	Mean Square	F	P
Within Samples	2	0.0780	0.0390	2.29	0.104ns
Between Systems	11	0.9525	0.0866	5.09	0.000***
Between Times	6	6.8161	1.0310	60.58	0.000***
Time * System interaction	66	5.5234	0.0837	4.92	0.000***
Error	166	2.8254	0.0170		
Total	251				
Levene's test for homogeneity of variance					0.995^{ns}

Table 6.5 Results of Two-way ANOVA on variations in the lignin content of leaf litter samples with respect to time and system

Source of variance	Degrees of Freedom	Sums of Squares	Mean Square	F	P
Within Samples	2	0.0008	0.0004	2.47	0.088^{ns}
Between Systems	11	0.0169	0.0015	8.86	0.000***
Between Times	6	0.0144	0.0024	13.81	0.000***
Time * System interaction	66	0.0299	0.0004	2.61	0.000***
Error	165	0.0287	0.0002		
Total	250				
Levene's test for homogeneity of variance					0.228^{ns}

Table 6.6 Results of Two-way ANOVA on variations in the cellulose content of leaf litter samples with respect to time and litter/system

Source of variance	Degrees of Freedom	Sums of Squares	Mean Square	F	P
Within Samples	2	0.0001	0.00006	1.73	0.181^{ns}
Between Systems	11	0.0039	0.0004	9.68	0.000***
Between Times	6	0.0179	0.0029	80.33	0.000***
Time * System interaction	66	0.0081	0.0001	3.33	0.000***
Error	166	0.0061	0.00004		
Total	251				
Levene's test for homogeneity of variance					0.127^{ns}

Table 6.7 Results of Two-way ANOVA on variations in the hemicellulose content of leaf litter samples with respect to time and system

Source of variance	Degrees of Freedom	Sums of Squares	Mean Square	F	P
Within Samples	2	0.00004	0.00002	0.38	0.686^{ns}
Between Systems	11	0.0044	0.0004	7.59	0.000***
Between Times	6	0.0144	0.0024	45.59	0.000***
Time * System interaction	66	0.0058	0.00008	1.70	0.004**
Error	166	0.0087	0.00005		
Total	251				
Levene's test for homogeneity of variance					0.872^{ns}

Table 7.1 ANOVA test for soil N and P at 0-15 and 15-30 cm depth

		N 0-15 (R^2=0.1938)	N 15-30 (R^2=0.7611)	P 0-15 (R^2=0.9362)	P 15-30 (R^2=0.7357)
Source of variation	d.f.	m.s.	m.s.	m.s.	m.s.
Systems	2	77.89	53.77	1205.3***	1162.67***
Sampling dates	6	228.74***	581.69***	1053.7***	70.04
Residual	52	50.34	41.86	154.6	67.12
Total	62	67.40	93.66	309.3	119.73

Note: *** indicates significative difference ($p \leq 0.001$)

Table 7.2 ANOVA test for soil Ca and K at 0-15 and 15-30 cm depth

		K 0-15 (R^2=0.7662)	K 15-30 (R^2=0.0534)	Ca 0-15 (R^2=0.187)	Ca 15-30 (R^2=0.187)
Source of variation	d.f.	m.s.	m.s.	m.s.	m.s.
Systems	2	78483831.***	58712863.***	1077088.	1382834.***
Sampling dates	6	35798661.	17822758.***	137447.	62404.
Residual	52	9347709.	3858614.	196461.	115789.
Total	62	14213924.	7480121.	287310.	212980.

Note: *** indicates significative difference ($p \leq 0.001$)

Table 7.3 ANOVA test for soil pH and S.O.M. % at 0-15 and 15-30 cm depth

		pH 0-15 (R^2=0.0167)	pH 15-30 (R^2=0.5029)	O.M. 0-15 (R^2=0.8551)	O.M. 15-30 (R^2=0.4445)
Source of variation	d.f.	m.s.	m.s.	m.s.	m.s.
Systems	2	0.01848	0.00937	1072.5***	959.15***
Sampling dates	6	0.03724	0.10715	532.1***	86.77
Residual	52	0.08103	0.08769	100.6	56.67
Total	62	0.08895	0.09655	173.1	93.43

Note: *** indicates significative difference ($p \leq 0.001$).