

Litter Decomposition Process in Coffee Agroforestry Systems

Judith Petit-Aldana¹, Mohammed Mahabubur Rahman^{2,3,*}, Conrado Parraguirre-Lezama⁴, Angel Infante-Cruz⁵ and Omar Romero-Arenas⁴

¹Faculty of Forestry and Environmental Science, University of the Andes, Mérida 5150, Venezuela

²Department of Horticulture, City Operations, Park and Road Services, City of Edmonton, Edmonton, Alberta T6X 1L6, Canada

³Education and Research Center for Subtropical Field Science, Faculty of Agriculture, Kochi University, Nankoku, Kochi 783-8502, Japan

⁴Natural Resources and Agroforestry Systems, Institute of Sciences, Benemérita Autonomous University of Puebla, Puebla 72000, México

⁵Research Department, Foundation for the Development of Science and Technology of the Merida State, Mérida 5150, Venezuela

Abstract

Decomposition of litter is a function of various interrelated variables, both biotic and abiotic factors. Litter decomposition acts like a natural fertilizer play a prime role in maintaining the productivity and nutrient cycling in agroforestry systems. There are few studies of decomposition carried out in agroforestry systems with coffee; so it is necessary to perform more research work to fill the research gap, which will allow a better understanding of the management of the coffee agroforestry systems. This paper is based on the theoretical and conceptual aspects of leaf litter decomposition in agroforestry systems, emphasizing the combination with coffee cultivation and critically examined the role of the different factors involved in the decomposition. This study made a comparison of different investigations with regards to weight loss, decomposition rates (k), initial chemical composition, and release of the main nutrients. This study suggested that it is necessary to implement studies of decomposition and mineralization, and the microflora and fauna associated with these processes, so that serves as an important tool to develop a model for enabling a description of the short, medium, and long-term dynamics of soil nutrients in coffee agroforestry systems.

Key Words: litter, decomposition, models, chemical composition, *Coffea arabica*

Introduction

The key process in nutrient recycling within ecosystems is decomposition, consisting of a series of physical and chemical processes by which leaf litter and foliage are reduced to their elemental chemical constituents (Aerts 1997). This is one of the most important events in ecosystems for their contribution of nutrients to the soil (Aber and Melillo 1991).

Decomposition is a set of processes in which dead organic matter is converted into its components: carbon dioxide,

mineral nutrients, and water. Knowledge of the decomposition of organic matter is of great importance in the management of areas under natural, agricultural, or silvicultural systems (Cardona and Sandeghian 2005).

In the agroforestry systems, nutrients enter through various sources such as rain, fertilizers, and organic residues, and these can accumulate either in the shade trees, cultivation, soil, or litter. At the same time, interactions occur between crop layers such as residue deposition, infiltration, absorption, and mineralization; likewise, outputs can occur by crops yields, leaching, runoff, and denitrification processes.

Received: April 5, 2018. Revised: April 23, 2019. Accepted: April 26, 2019.

Corresponding author: Mohammed Mahabubur Rahman

Department of Horticulture, City Operations, Park and Road Services, City of Edmonton, Edmonton, Alberta T6X 1L6, Canada
Tel: +1 780 988 0023, Fax: +1 780 807 8608, E-mail: mahabubtarek1976@yahoo.ca

The study of the nutrient cycle in coffee agroecosystems is fundamental to understand the dynamics of the elements and their availability in the sustainable management of the productive system. Thus, as in several studies of the different components of the nutrient cycle, the input of the organic material to the agricultural systems and their rate of decomposition have been analyzed and emphasizing that these phenomena determine the availability of nutrients and, therefore, productivity.

The dynamics of litter in coffee agroforestry systems is essential for understanding the functioning of the system and for assessing its impact on the environment. It is also significant because it provides the information needed to establish management practices for restoration of degraded areas and maintaining productivity in areas created (Duarte et al. 2013).

Agroforestry is considered to maintain nutrient recycling more effectively than agriculture. This hypothesis is based in part of the studies on the efficient recycling of nutrients from leaves of trees in natural ecosystems and on the assumption that agroforestry trees also transfer nutrients to intercropping. Currently, greater importance is being given to the study of the contribution of minerals through the decomposition of organic matter offered by leguminous and non-leguminous trees in agroforestry systems. The trees are able to maintain or increase soil fertility through nutrient recycling; in other words, they achieve the maintenance of soil organic matter through the production and decomposition of litter and pruning residues (Petit-Aldana et al. 2012). Although there have been many studies of decomposition and nutrient release in the tropics, there are few studies of decomposition made in agroforestry systems (Teklay and Malmer 2004). Thus it is important to study on decomposition of agroforestry systems. The objective of this study is based on a descriptive and analytical exploration, where theoretical and conceptual ideas on litter decomposition in agroforestry systems are systematically contextualized, emphasizing the combination with coffee cultivation. This paper has analyzed the decomposition of leaf litter as a complex set of processes involving chemical, physical, and biological agents; decomposition rates; and study models, among others. We subsequently discuss the decomposition process in agroforestry systems with an emphasis on coffee plantations, making comparisons of vari-

ous investigations regarding weight loss, decomposition rates (k), initial chemical composition, and release of the major nutrients.

Litter Decomposition: A Set of Different Processes

The process of "litter decomposition" is quantitatively as important as photosynthesis. This process is necessary for the recirculation of the nutrients and the continuous accumulation of biomass of the plants, as well as for maintaining food webs through the energy released by the degradation of organic matter compounds (Berg 2014).

Decomposition is a set of processes, including leaching, fragmentation, ingestion, excretion of waste products, and changes in physical and chemical structure. These processes are carried out by a great variety of decomposing organisms, mainly by bacteria, fungi, and detritivores. Bacteria are the dominant decomposers of dead animal matter, while fungi are the most important decomposers of dead plant material. The main process called "litter decomposition" is extremely complex and can be subdivided into a multitude of subprocesses. These include not only the release of nutrients but also a gradual degradation of the major chemical compounds present in the mulch resulting in new compounds, which in turn can recombine, often creating the reluctance in the remnant mass of litter. Despite its importance, this system of subprocesses is mainly unknown (Berg 2014).

The litter decomposition involves a complex series of processes including chemical, physical, and biological agents acting on a wide variety of organic substrates that are constantly changing. Decomposition in a natural environment can be described in general terms only because of the vast diversity of possible factors and interactions. Despite this complexity, several important processes are involved and general trends can be outlined (Berg and McLaugherty 2003).

The concept of "litter" is wide with respect to the components and chemical composition and leaf litter seems to be the fraction that has been most studied. Even the leaf litter of different species has different chemical compositions, so they are expected to exhibit different patterns of decomposition between species or at least between genera. Also,

the bark, branches, roots, and leaf litter of the same plant may have different chemical compositions and, therefore, follow different decomposition patterns (Berg 2014).

The litter produces an organic layer on the surface of the soil, resulting in a characteristic edaphic microclimate and suitable conditions for a broader group of organisms. Decomposition contributes to the regulation of the nutrient cycle and primary productivity, as well as the maintenance of forest soil fertility (Wang et al. 2008). As a process, decomposition is essential to the functioning of forests. If nutrients are released quickly, they can be lost by leaching or volatilization. In contrast, if decomposition is very slow, the capital of nutrients available to plants may be insufficient and limit the growth and development (Swift and Anderson 1989; Montagnini and Jordan 2002).

The general pattern for weight loss of decomposing litter is comprised of two phases: an initial rapid development by washing soluble compounds and decomposition of labile materials (e.g., sugars, some phenols, starch, and protein) and a second phase as a result of the slow decomposition of recalcitrant elements such as cellulose, hemicellulose, tannins, and lignin (Goma-Tchimbakala and Bernhard-Reversat 2006). On the other hand, during the decomposition of the organic matter, three phases can be differentiated for the release of nutrients: an initial rapid release of soluble components, in which the washing processes dominate, followed by a phase of immobilization, and finally a phase of net release (Weerakkody and Parkinson 2006a).

This release can take several paths depending on different factors such as humidity, temperature, nutrient availability in the soil, species, age, and litter quality (e.g., N and P concentrations, C:N and N:P ratios, lignin content, tannins, etc.). The quality characteristics of litter can determine in turn the microbial biomass and mineralization of nutrients (Dutta and Agrawal 2001; Weerakkody and Parkinson 2006b).

Leaf litter decomposition is an important link in the biogeochemical cycles within forest and agroforestry ecosystems; it is a source of energy for the microorganisms that inhabit them (Swift et al. 1979) and thus determines the quality of the soil. Studies conducted by Di Stefano and Fournier (2005) have shown that the product of the decomposition of litter could annually generate between 69% and

87% of the energy for the growth of forests and agroforestry systems. Soil biotic activity is the driving force for the transformation of organic matter in soil litter and soil development and maintenance. Decomposition phases differ in each of the components and are influenced by abiotic factors such as soil temperature, humidity, aeration, and the quality of the litterfall.

The leaf litter decomposition rates are influenced by at least three general factors: the composition and activity of the community of decomposers, the quantitative characteristics of leaf litter, and the physical-chemical environment (Swift and Anderson 1989; Kavvadias et al. 2001). The type of species has a great influence on the rate of decomposition (k), most likely through its influence on the quality of the leaves and morphology (Salinas et al. 2011).

One way to measure the rate of decomposition and nutrient release of leaf litter, which falls to the forest floor, is the method of litter bags, which allows a measure of the mass loss under natural conditions (Kurz-Besson et al. 2005). This mass loss is regulated by climate, soil conditions, soil community, and quality of plant material (Anderson et al. 1989; Aerts 1997; Coûteaux et al. 2001). Climate level, temperature, and humidity are the main environmental factors affecting the decomposition process (Swift and Anderson 1989; Lavelle et al. 1993). Humidity influences not only the leaching of nutrients but also creates the appropriate conditions for the activities of soil microorganisms and invertebrates (Swift and Anderson 1989; Tietema and Wessel 1994). These generally are associated with dead plant material and are the ones that ultimately regulate the decomposition process but its activity depends on soil conditions and the quality or chemical characteristics of the plant material. The latter is given by the concentration of nutrients such as nitrogen, phosphorus, potassium, carbon, calcium, and biochemical compounds such as lignin, cellulose, hemicellulose, polyphenols, and tannins (Swift et al. 1979). The initial content of some of these inorganic and organic fractions, such as the initial concentration of nitrogen, the carbon/nitrogen ratio (C:N) (Flanagan and van Cleve 1983; Handayanto et al. 1994), lignin content (Berg and McLaugherty 2014), lignin/nitrogen ratio (L:N) (Melillo et al. 1982), and the soluble phenols (Tian et al. 1992) determine the dynamics of weight loss of plant material.

The decomposition is performed by a complex community that includes soil microflora and soil fauna. Bacteria and fungi are primarily responsible for the biochemical processes in the decomposition of organic waste because they produce enzymes that degrade complex molecules. About 80% of the degradation of plant material is carried out by microorganisms, fungi being one of the main agents (Lavelle and Spain 2005). Additionally, the soil fauna is responsible for fragmenting plant residues and increases biodegradation. They can alter the primary production, soil structure, and patterns of microbial activity, organic matter dynamics, and nutrient cycling (Coleman et al. 2004).

Table 1 shows some of the models found in the literature for the study of litter decomposition; they can be divided into two main categories. The first group is comprised of those describing the complete decomposition of litter and is based on the assumption that the litter is fully decomposed and has fixed rates of decomposition. The second group of models is based on the supposition that the litter decomposes at an extremely low speed or not at all, as has been proposed by a large number of equations involving various considerations (Berg and McClaugherty 2014).

The first approach was the simple exponential model (Jenny et al. 1949; Olson 1963) and is still the most widespread. This model assumes that the decomposition rate is constant over time, so dynamic decomposition strong decreasing curvature cannot be adjusted at the same. In response to the two phases of the dynamic natural decomposition, the double exponential model, which normally improves the simple exponential model, is designed and their use has also been broad (Lousier and Parkinson 1976; Wieder and Lang 1982; Coûteaux et al. 2001). Similar fea-

tures found in the asymptotic model, which also considers the two stages of decomposition and assumes that degradation will stabilize around a value greater than zero (Howard and Howard 1974; Lousier and Parkinson 1976; Aponte et al. 2012). Other models are the linear model (Lang 1973), the quadratic model (Lang 1973; Howard and Howard 1974; Pal and Broadbent 1975), and the power model (Van Cleve 1971; Pal and Broadbent 1975). Recently, new models have been proposed, some of which require more mathematical complexity (Forney and Rothman 2007; Feng 2009; Rovira and Rovira 2010).

When taking into the account of the different approaches, it is important to consider that the modeling of the decomposition the process is intended to have realistic mathematical expressions and biological terms (Table 1).

The important factor in the process of litter decomposition is chemical composition. It is well established that the chemical nature of litter affects decomposition rates in forest ecosystems (Swift et al. 1979; Aber et al. 1990, Rahman et al. 2017).

In general, the quality of the litter is often related to the chemical characteristics such as the C: N ratio and the content of carbon, nitrogen, lignin, condensed tannins, hydrolyzable tannins, phenols, and carbohydrates (e.g., cellulose and hemicellulose) (Rahman and Motiur 2012; Rahman et al. 2017) (Table 2). The chemistry of litter decomposition is a crucial component of global biogeochemical cycles that affect soil fertility, destination and residence times of the carbon and reservoirs of organic matter and nutrients in organic production, and ultimately the composition and production of plant communities (Wardle et al. 1997; Rahman et al. 2017).

Table 1. Some models used to describe the decomposition of litter (M_t as the proportion of initial (M_0) mass remaining at time t ; A and C are constants; k is decay constants) (adapted from Berg and McClaugherty (2014) and Wieder and Lang (1982))

Expression	Model	References
$M_t = A + Br^t$	Asymptotic	Howard and Howard (1974)
$M_t = M_0 e^{-kt} + S$	Asymptotic	Berg and Ekbohm (1991)
$L_t = m (1 - e^{-kt/m})$	Asymptotic	Harmon et al. (2000)
$M_t = M_0 e^{-kt}$	Single exponential	Jenny et al. (1949), Olson (1963)
$M_t = A e^{-k_1 t} + B e^{-k_2 t}$	Double exponential	Bunnell et al. (1977), Lousier and Parkinson (1976)
$M_t = C - kt$	Linear	Woodwell and Marples (1968), Lang (1973), Howard and Howard (1974)
$M_t = C + k_1 t + k_2 t^2$	Quadratic	Lang (1973), Howard and Howard (1974), Pal and Broadbent (1975)
$M_t = C t^k [k < 0]$	Power	Van Cleve (1971), Howard and Howard (1974), Pal and Broadbent (1975)

Table 2. Litter chemical traits and relation to litter quality and decomposition rate (adapted from Rahman et al. 2017)

Litter organic chemical traits	Litter quality	Relationship with decomposition
Lignin	Positive relation with lignin concentration, litter fiber component and lignin: nitrogen ratio	Negative relation to litter decomposition rate
Tannin (condensed tannins, hydrolyzable tannins)	Positive relation to tannin concentration	Negative relation to litter decomposition rate
Total phenolics	Positive relation to total phenol concentration	Negative relation to litter decomposition rate
Carbohydrates (celluloses, and hemicellulose)	Positive relation to cellulose concentration, hemicelluloses concentration and holocellulose: hemicelluloses ratio	Positive relation to litter decomposition rate
Nitrogen content	Positive relation to litter N concentration Negative relation with lignin and lignin: N ratio	Positive relation to litter decomposition rate
Carbon content	Positive relation with lignin and lignin: N	Negative relation to litter decomposition

Process of Litter Decomposition in Agroforestry Systems

One of the main investigated ways of improving soil fertility in tropical agroforestry systems is the recycling of nutrients through the decomposition of tree biomass, mainly leaf litter or pruning remains and also of roots that are added to the soil. The benefits that are obtained are indisputable and depend on the quantity and nutrient content of the biomass added and the rate at which it decomposes. A huge amount of information is available on the nutrient content and the amount of biomass produced by different trees and shrubs used in agroforestry systems under a variety of conditions, especially in systems such as alley cropping and improved fallows, where improving soil fertility are an important goal. As expected, there is considerable variation in this data (Nair et al. 1999).

The tree component in an agroforestry system seeks to optimize the use of resources and increase productivity per unit area. Besides being a source of energy, wood, fruits, or shade, trees can regulate the lighting conditions for the main crop and replace part of the required nutrients required; likewise, a sufficient density of trees are able to reduce the effect of strong winds, which contributes to the protection of the soil and crop. Trees also provide lots of plant residues, which act as cover material (López-Gutiérrez et al. 2001). The litter layer is the link that holds the tree components with the ground and this layer, in turn, releases nutrients that can be absorbed by plants again through the processes of decomposition and mineralization (Staver et al.

2001).

The decomposition has four stages (Singh and Gupta 1977); 1) grinding, which is the fractionation of tissues; 2) leaching, which refers to the loss of the more soluble compounds by water currents; 3) catabolism (including mineralization and humification), which is the transformation that takes the microflora of organic compounds to organic form allowing nutrients to be used again by plants and, thus, complete the cycle of nutrients; and 4) humification, which is the neo-formation of organic matter by microorganisms.

These phases occur simultaneously and, at the end of the process, microorganisms use carbon compounds for both biosynthesis and energy supply (Paul and Clark 1996). Thus, the latest product of the breakdown of soil organic matter is carbon dioxide, which is sufficiently ventilated so that the production of carbon dioxide can be used as an indicator of decomposition rates.

Weather conditions significantly influence the decomposition of litter in a large geographical scale. Therefore, in tropical humid regions decomposition is considered to be faster than in the temperate regions, though decomposition rates vary widely in different climatic regions (Hirobe et al. 2004). The relationship of soil fauna with increased decomposition rates has been demonstrated and, while the speed of this process varies according to the type of vegetation. There is no evidence found that fauna (macrofauna and microfauna) contribute differentially to the breakdown of leaf litter (Slade and Riutta 2012).

The chemical composition of the litter is essential for de-

composition and nutrient cycling in forest systems (Aerts and de Caluwe 1997; Hättenschwiler and Vitousek 2000) and is characterized as being highly dynamic since the concentrations of cellulose, hemicellulose, and lignin are known to change during the decomposition (Berg et al. 1982). In some cases, tannins and phenolics are lost rapidly in litter decomposition (Baldwin and Schultz 1984; Pereira et al. 1998). Consequently, changes in the concentrations of phenolic compounds and lignin during the early stages of decomposition are important because they can be included in subsequent rates of this process and in later stages (Wilson et al. 1986).

Likewise, different authors (Russo and Budowski 1986; Petit-Aldana et al. 2012) have demonstrated the potential of agroforestry systems to bring biomass and recycle nutrients from decomposing litter, which may be affected by tree species used for shade, to the extent that they differ significantly in the production of biomass, the rate of decomposition, and the production of root biomass (DaMatta and Rodríguez 2007).

On the other hand, shade trees protect the soil from direct insolation, help maintain organic matter, reduce evaporation, and maintain soil productivity (Siebert 2002). Soil moisture benefits the biota and the process of decomposition. Leaf litter of different species (shade crops and trees) affects the decomposing community structure, leaf litter decomposition, and soil nutrient fluxes. In Indonesia, the annual production of litter from trees of the legume *Gliricidia sepium* amounts to 3.9 tons per hectare per year (Moser et al. 2010).

The increase in litter shade trees promotes a diversity of decomposer organisms and other species can provide ecosystem services such as pest control. Decomposers also form an important link in the cycles of nitrogen and phosphorus ecosystems. A study on the changes and availability of soil N in cocoa agroforestry systems in Indonesia reported higher rates of N mineralization, absorption of ammonia, and the rapid return to the reservoir of ammonium in a *Zea mays* monoculture adjacent, which demonstrates greater availability of N in agroforestry combinations (Corre et al. 2006). This suggests that in contrast to the monoculture of corn, the decomposer community in cocoa agroforestry maintains most of its functions through nutrient recycling.

Overall, soil erosion is negligible in cocoa agroforestry systems and nutrient losses are negligible at least in plots situated on steep slopes (Hartemink 2005). Shade trees play an important role in controlling erosion because they protect the soil from the impact of rain, reducing runoff velocity by increasing surface roughness, water infiltration, as well as providing a layer of mulch so that tree roots create channels within the soil.

Decomposition in Coffee Agroforestry Systems

A coffee agroforestry system is a set of crop management practices, where tree species are combined in association with coffee. The objectives of this agroforestry system are the management and conservation of soil and water and the increase of production and ensure sustainability and strengthening the coffee families' social and economic development (Farfan 2014).

The potential ecological interactions in a coffee agroforestry system are numerous. The results of interactions can be positive, negative and neutral.

Fig. 1 shows a summary of the various interactions between components in the agroforestry system. There are two types of coffee agroforestry systems such as simple and stratified. When the shade the coffee ecosystem is composed of a single species it is called a simple agroforestry system and when the tree component is composed of more than two species it qualifies as a stratified coffee agroforestry system (Farfan 2014).

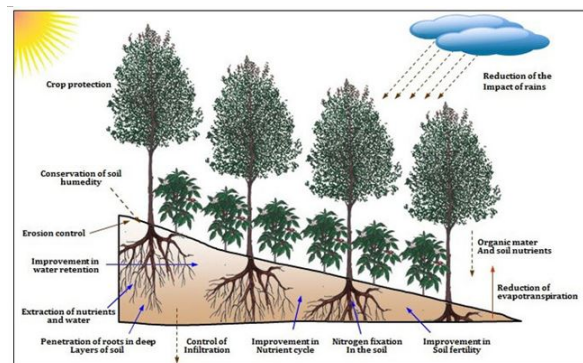


Fig. 1. Ecological interactions in coffee agroforestry system (adapted from Farfán, 2013 <https://agroforestryandcoffee.jimdo.com/>).

Although there is scientific literature documenting the process of litter decomposition in coffee plantations, it is oriented towards the decomposition of litter shade trees and the use of green manure (mulch) applied to the crop. Based on this information, this paper is presenting a review of research work according to weight loss, decomposition rates (k), initial chemical composition, and release of the major nutrients.

Decomposition rates (k) and weight loss

The decomposition rate can be considered more consistent than the remaining weight at a given time parameter because it can integrate into a single value the effect of time on the decomposition process and infer accurately on the decomposition of a given substrate and comparison between treatments. In addition, decomposition rates eliminate contamination errors of samples that may exist due to microclimatic site conditions, adhered soil, etc., which influence the observed weight, errors that are leveled with the decomposition curves modeled under a linear and the exponential model (Isaac et al. 2005).

In Costa Rica, Vilas et al. (1993) studied during the period of October 1989 to June 1990, the rates of decomposition, nutrient release, and change in the cell wall of litter in agroforestry plots with perennial crops: coffee (*Coffea arabica*) associated with leguminous shade trees poro (*Erythrina poeppigiana*); coffee with shade timber trees laurel (*Cordia alliodora*); cocoa (*Theobroma cacao*) with laurel, poró, and cocoa. The cocoa leaf litter/laurel system showed a slow decomposition: the loss was only 32% of initial weight. The leaf litter of the cocoa/poro, coffee/laurel and coffee/poro systems presented faster losses: 47%, 49%, and 58%, respectively. Apparently, the factors that contributed to these differences were the physical-chemical characteristics of the litter. The authors did not report leaf litter decomposition rates (k).

Arellano et al. (2004) conducted an experiment for 224 days in Trujillo, Venezuela, where the litter decomposition rate was evaluated in three coffee agroecosystems (*Coffea arabica*): coffee with tree shade of *Inga* sp (CT), coffee with fruit trees *Citrus sinensis* (CF), and coffee in full sunlight (CS). They reported that weight losses were rapid at the beginning of the experiment. Then from 125 days onward,

the curves of weight loss were parallel to the time axis, indicating a slow decomposition. At the end of the experiment (224 days), as decomposition corresponds to the leaves placed on the agroecosystem CF, the remaining weight was 25%. For agro-ecosystems, CT and CS was 36% and 28%, respectively. On the other hand, the greatest value of the constant decomposition presented in litter agroecosystem CF ($k=2.79$) with a half-life time ($t_{1/2}$) of approximately 90 days, followed by the CT ($k=2.60$) with a $t_{1/2}=97$ days, and the shortest in the CS ($k=1.41$) with a $t_{1/2}=179$ days. They concluded that the agroecosystem coffee with fruit (CN) is the one that has the highest rate of decomposition.

Mungia et al. (2004) selected two plantations four years old of *Coffea arabica* cv. Costa Rica 95 (5000 plants ha^{-1}), shaded by *Eucalyptus deglupta* (278 trees ha^{-1}), on the farms Verde Vigor and Santa Fe, located in the southern zone of Costa Rica, placing litterbags under the coffee trees. Treatments consisted of freshly fallen leaves of *E. deglupta* and/or *C. arabica* and/or green leaves of *Erythrina poeppigiana* prunings (alone or in mixtures), which were collected at 0, 6, 12, 24, 48, 72, 96, 150, and 213 days of exposure. In the Verde Vigor farm, the litter decomposition of *E. deglupta* alone showed the lowest rate of decomposition with respect to other treatments with a weight loss of 23% at 213 days ($k=0.08$), *E. poeppigiana* alone had the highest rate, with 86% decomposition of the material in the same period ($k=0.58$). The mixtures with *E. poeppigiana* had a rate of 59%. On the other hand, in the Santa Fe farm, the decomposition rate of *C. arabica* (60% of the material to 213 days; $k=0.30$) was higher than in *E. deglupta* or the mixture of both, with 39% and 47%, respectively. Likewise, the decomposition of *C. arabica* in mixture with *E. deglupta* on the Verde Vigor farm was faster when *E. poeppigiana* (40% $k=0.198$) was included. *E. poeppigiana* with the litter of *E. deglupta* accelerated the rate of decomposition (60% $k=0.556$). The decomposition of the green leaves of *E. poeppigiana* was not affected by the presence of other species.

Cardona and Sadeghian (2005) investigated the decomposition process in coffee agroforestry systems with *Inga* sp. and free coffee at full sunlight at two locations in Colombia for a year. For weight loss, it was found that coffee litter presented faster decomposition front *Inga* sp., especially under

shade, at the end of the experiment showed a weight loss of 78% for coffee under the shade, 71% for coffee at full sunlight, and 49% for *Inga* sp. Decomposition rates from leaves coffee under shady and sun exposure were equal to each other and statistically different from *Inga* sp., in the two study sites. The authors argued that the values of k were the first reported in the country for the two species tested and the reason why there are no data to serve as a comparison parameter. However, they said that the decomposition results match the records of literature for organic matter in the Colombian coffee zone, where the litter produced by coffee was classified as a material rapid decomposition. They concluded that the difference between decomposition rates was important because of the final effect generated by the various materials. The rapid degradation of coffee residues as a result of its composition provided crop nutrients in a shorter period. Residues from *Inga* sp., however, suffer a different process due to their higher lignin content, in that case the main product of decomposition was humus, the most abundant and important fraction of the stable organic matter in the soil. The annual return of nutrients (kg ha^{-1}) in the organic material of N, P, and K were 1.99, 0.08, and 0.49, respectively.

In a study in Carazo, Nicaragua by Flores et al. (2006), for 96 days the litter decomposition in two environments and three treatments were evaluated: *Coffea arabica* with fertilization under shadow of *Gliricidia sepium* (C+Gs f); *C. arabica* without fertilization under *G. sepium* (C+Gs wf); and *C. arabica* under full sun exposure (C). It was observed that the weight losses were faster at the beginning of the decomposition in plots under shade and slower in coffee in full sunlight. At the end of the experiment, the greatest weight loss (50%) corresponded to treatment C+Gs f, followed by C+Gs wf (40%) and C (35%). Decomposition was also greater for C+Gs f, with a constant of decomposition

($k=0.07$), which was higher than the other treatments.

Farfan and Urrego (2007) evaluated the decomposition of dry matter and the nutrient transfer of the species *Cordia alliodora*, *Pinus oocarpa*, and *Eucalyptus grandis* in agroforestry systems with coffee in Colombia. The plant material for analysis of the rate of decomposition of dry matter produced by the coffee under each cropping system and produced by *C. alliodora*, *P. oocarpa*, and *E. grandis*, was obtained directly from the coffee plants and trees, samples were collected at 30, 180, and 365 days. Weight losses for coffee and decomposition rates are observed in Table 3.

The culture system of coffee under shade or full light does not affect the rate of decomposition of the plant residues. At the beginning of the decomposition, weight loss coffee was slow in association with *P. oocarpa* (1%), then 180 days greater weight loss corresponded to the association with *P. oocarpa* and lower with *E. grandis*, and 365 days after 70% of the initial weight was incorporated into the soil. The loss of mass in the forest species at the end of the experiment followed the sequence *C. alliodora* > *E. grandis* > *P. oocarpa*. The authors argue that no statistical differences were shown between the annual decomposition rate for the coffee in full light and under shade. This difference in the decomposition rate of the residues of *C. alliodora* and *E. grandis* was not evident either, but there was a statistical difference between the rate of decomposition of plant residues *P. oocarpa* and coffee in all its environments and *E. grandis* and *C. alliodora*. In other words, pine plant residues decompose more slowly than the other materials. The culture system coffee under shade or sun exposure does not affect the rate of decomposition of the plant residues.

Villavicencio-Enrígez (2012) conducted a study to analyze the production, weight loss and decomposition rates of litter in agroforestry plots with Traditional System Coffee

Table 3. Weight loss (%) and decay constants (k/year) coffee free solar exposure and agroforestry arrangements with *Cordia alliodora*, *Pinus oocarpa* and *Eucalyptus grandis* (adapted from Farfan and Urrego 2007)

Days	Coffee unshaded	k	Coffee+ <i>C. alliodora</i>	k	<i>C. alliodora</i>	k	Coffee+ <i>P. oocarpa</i>	k	<i>P. oocarpa</i>	k	Coffee+ <i>E. grandis</i>	k	<i>E. grandis</i>	k
30	7	1.0	10	1.0	6	0.8	7	0.9	1	0.3	6	1.1	2	0.7
180	40		49		40		51		22		38		37	
365	66		67		59		63		25		70		58	

(TSC), Rustic Systems Coffee (RSC), and Medium Tropical Forest (MTF), in San Miguel, Veracruz, Mexico. To measure the decomposition, prepared 252 bags of polyethylene of dominant species and mixtures representative per system (Table 4), samples were collected in seven dates for 352 days. Weight loss of litter during the dry season (January to June), showed accelerated weight loss and a consequent slowdown during the rainy season (July to December). The average weight loss during the dry season (0-176 days) was 65% and during the rainy season (176-352 days) was 17%. On the other hand, similar trends of decomposition rates were observed in the bags containing *R. mirandae/C. arabica* and mixed leaf litter. During the first 176 days, rapid weight loss and slower decomposition of remaining weight in the TSC (34.7% and 39.3%) and MTF (43.3% and 33.3%) was observed. In the RSC treatment, weight remnants of *R. mirandae/C. arabica* and mixture of litter followed the same trend in the first 176 days, but showed differences in weight loss to 352 days only 8% (the highest weight loss) and 12.7%, respectively, for each species.

Weight loss for mixing *R. mirandae/C. arabica* was 55% to 62% during the dry season in the three systems. During the rainy season the greatest weight loss was observed in RSC at 87% compared to 67% at 352 days in TSC and MTF. The leaf litter mixture showed different loss patterns in the three systems, following the order of TSC > Smsp > RSC with losses of 60%, 64%, and 92%, respectively. In all systems, the remaining dry weight varied in the following order: *R. mirandae* > *R. mirandae/C. Arabica* > Leaf litter mix > Dominant species (*P. hispidum* > *C. officinalis* > *M. capirii*).

The decomposition rates for all species varied from

-0.1278 (*R. mirandae/C. arabica*, in MTF) to 3.912 (*P. hispidum*). The k values were comparatively higher in the entire litter tested in the last 176 days of incubation. The decomposition rate was high for *Piper hispidum* and litter in RSC, indicating a possible effect of microclimate or quality litter. The lowest rates were obtained in *Robinsonella mirandae/Coffea arabica* and *Mastichodendron capirii* in TSC and MTF.

The author argues that a rapid initial k was followed by a slower rate and shows that the decomposition the process is divided into two phases controlled by different factors: an initial phase with a faster rate of k by weight followed by a phase with slower rates of decomposition, which is consistent with the results reported by other authors (Swift and Anderson 1989; Xuluc-Tolosa et al. 2003). The author concluded litter quality and different mixtures of trees are the main drivers of the decomposition process in the native agroforestry systems. Legumes used as green manure are considered an important source in the coffee plantations, especially for the low availability of nutrients. da Matos et al. (2011) conducted field experiments to assess rates of decomposition and release of nutrients in legumes used as green manure in an agroforestry system with coffee, on two farms (*Pedra Dourada* (PD) and *Araponga* (ARA)) different climatic conditions in the Zona da Mata of Minas Gerais, Brazil with four legume species: *Arachis pintoii*, *C. muconoides*, *Stizolobium aterrimum*, and *Stylosanthes guianensis*. Litterbags under coffee bushes were placed and collected at 15, 30, 60, 120, 240, and 360 days. The greatest losses of dry biomass occurred from 0 to 15 days, with at least 20% of the dry biomass of leguminous plants being

Table 4. Leaf litter content in litterbags to obtain the decomposition per system. San Miguel Veracruz, Mexico (Adapted from Villavicencio-Enríquez 2012)

TCS	RCS	MTF
<i>Robinsonella mirandae</i>	<i>Robinsonella mirandae</i>	<i>Robinsonella mirandae</i>
<i>Robinsonella-mirandae/Coffea arabica</i>	<i>Robinsonella-mirandae/Coffea arabica</i>	<i>Robinsonella-mirandae/Coffea arabica</i>
<i>Mastichodendron capirii</i>	<i>Piper hispidum</i>	<i>Croton officinalis</i>
Litter mixture	Litter mixture	Litter mixture

TCS, traditional coffee system; RCS, rustic coffee system; MTF, medium tropical forest. Mixture, leaf litter mixture per system.

Table 5. Initial chemical composition of the leaves of some coffee agroforestry systems

Specie/ combination	Country	Chemical composition											References	
		%N	%C	%P	%K	%Ca	%Mg	%L	%PF	C:N	C:P	L:N		(L+PF)/ N
<i>Coffea arabica</i>	Costa Rica	1.93	-	0.11	1.98	-	-	44	3	-	-	-	-	Mungia et al. 2004
<i>Eucalyptus</i>		0.90		0.06	0.79	-	-	38	8	-	-	-	-	
<i>deglupta</i>														
<i>Erythrina</i>		5.74		0.40	2.30	-	-	34	2	-	-	-	-	
<i>poepigiana</i>														
<i>Coffea arabica</i>	Colombia	1,7	53.4	0.19	1.23	1.70	0.33	-	-	32.2	-	-	-	Farfan & Urrego 2007
<i>Cordia</i>		2.0	47.1	0.07	0.80	5.50	0.80	-	-	23.8	-	-	-	
<i>alliodora</i>														
<i>Pinus occarpa</i>		0.5	55.7	0.02	0.18	0.45	0.06	-	-	105.1	-	-	-	
<i>Eucalyptus grandis</i>		0.8	55.2	0.05	0.59	1.07	0.14	-	-	71.7	-	-	-	
Café with shade		2.8	53.3	0.21	1.25	1.72	0.35	-	-	24.9	-	-	-	
<i>C. arabica</i>	Colombia	2.19	-	0.14	0.60	1.57	0.24	-	-	-	-	-	-	Cardona & Sadeghian 2005
Café with shade (<i>C. arabica</i> + <i>Inga codonantha</i>)		2.08	-	0.10	0.25	1.91	0.16	-	-	-	-	-	-	
<i>Inga subnuda</i>		3.20	-	0.14	-	-	-	27.3	4.8	16	357	8.5	10.0	
<i>Persea americana</i>		2.10	-	0.16	-	-	-	21.0	7.3	24	313	10.0	13.5	
<i>Senna macranthera</i>	Brasil	2.96	49.6	0.28	0.99	0.98	0.26	19.4	7.7	16.8	173.8	6.4	-	Jaramillo 2007
Mulch <i>Arachis pinto</i>	Brasil	2.65	-	0.26	2.30	-	-	8.1	1.8	15.8	164	3.1	3.8	da Matos et al. 2011
Mulch <i>Calopogonium mucunoides</i>		3.31	-	0.27	2.20	-	-	8.4	1.3	13.1	156	2.6	2.9	
Mulch <i>Stylosanthes guianensis</i>		3.08	-	0.20	2.00	-	-	5.5	1.6	14.1	170	1.8	2.3	
Mulch <i>Stizolobium aterrimum</i>		3.63	-	0.26	2.01	-	-	9.6	3.9	12.3	175	2.6	3.2	
<i>Aegiphila selloviana</i>	Brasil	3.80	-	0.19	-	-	-	18.2	4.9	13	263	4.8	6.1	Duarte et al. 2013
<i>Erythrina verna</i>		3.30	-	0.18	-	-	-	7.70	6.4	15	278	2.3	4.3	
<i>Luehea grandiflora</i>		2.00	-	0.12	-	-	-	13.6	8.3	25	417	6.8	11.0	
<i>Senna macranthera</i>		3.60	-	0.19	-	-	-	15.4	7.6	14	263	4.3	6.4	
<i>Zeyheria tuberculosa</i>		2.20	-	0.11	-	-	-	14.5	4.4	23	455	6.6	8.6	
Coffee with shade (some species)	Colombia	1.68	53.3	-	-	-	-	25.7	-	34	-	15.3	-	Díaz 2009
Coffee unshaded		1.69	53.8	-	-	-	-	19.5	-	32	-	11.8	-	

decomposed in both areas. In this interval, the decomposition of spontaneous vegetation was greater than that of leguminous plants in PD (50%) and less than that in ARA (10%). In general, the rates of decomposition of all plants decreased after 120 days, except for the spontaneous vege-

tation in ARA, which showed a sharp increase in the decomposition rate after 120 days. The biomass decomposed was greater in PD than in ARA at the end of the experiment and greater for spontaneous vegetation than for the leguminous plants.

The decomposition coefficients were estimated by the linear regression equation ($X_t = a - kt$, where X_t is the dry weight at time t and k represents the decomposition constant. The constant a is the initial quantity of dry biomass added in the litterbags. The slope k represents the decomposition rate and the mean half-life ($t_{1/2}$) by $\ln(2)/k$). In the *Pedra Dourada* farm, decomposition rates followed the order *C. mucunoides* < *S. aterrimum* < *S. guianensis* < *A. pintoii*, while in the *Araponga* farm there was no difference in the rate of decomposition between legumes (k between 0.0022 to -0.0030). On the average, rates of decomposition of residue in *Araponga* were 50.7% lower than the *Pedra Dourada*. Except for *C. mucunoides*, the half life ($t_{1/2}$) of the legume species in the first was 57% shorter than in the second farm. At the end of the process (360 days), decomposition rates tend to decrease due to the accumulation of recalcitrant components, increasing the difference between the two farms. The authors concluded that in general decomposition rates tend to be higher in the south-facing area, resulting in increased humidity in the coffee plantation in the area facing west.

Initial Chemical Composition

The litter chemical composition is the most important factor of litter decomposition. Teeney and Waksman (1929) pointed to the initial chemical composition as the main factor controlling the rate of decomposition. Although decomposition rates vary strongly with the climate, the immobilization of nitrogen in leaf litter and its output in mineral forms are mainly controlled by the initial chemical composition of vegetable residues. Within an ecosystem, the quality of the litter is the most important factor in determining the rate of decomposition (Cadisch and Giller 1997). However, there is considerable interspecific variation in the quality and quantity of litter that different species of plants produce; therefore, decomposition (both nutrients and carbon cycle) is strongly determined by the characteristics of the litter of the dominant species in an ecosystem (Hoorens et al. 2003).

Table 5 shows the initial chemical composition of the leaves of some coffee agroforestry systems in Costa Rica, Colombia, and Brazil. It is observed that the contents of the different elements vary according to location and species

studied. Overall, the initial concentrations of the elements are within the ranges reported.

Nutrient Release

Decomposition and nutrient release of leaf litter are key to ensuring the proper functioning of the biogeochemical cycle's processes and encourage appropriate physical, chemical, and biological soil conditions. The release of elements from the litter through the decomposition process represents one of the main processes of nutrient cycling in forestry and agroforestry ecosystems. The decomposition and mineralization regulate the availability of nutrients, organic matter accumulation, and growth of forests (Montagnini and Jordan 2002). After the mechanical and physical destruction of the plant remains, attack by microorganisms based on their digestive juices and enzymes, leading to the destruction of the organic components and the release of minerals, occurs. The release of nutrients during litter decomposition is one of the most important processes that contribute to nutrient cycling in agroecosystems. It is a process that can take hours or months depending on multiple factors such as climatic and soil conditions, plant species, age, and density of populations, where the fixation rate can vary widely depending on the setting process and microorganisms.

Nitrogen (N), Organic Carbon (CO), and Carbon:Nitrogen Ratio (C:N) Release

The importance of nitrogen to plants is accentuated by the fact that only carbon, hydrogen, and oxygen are more prevalent in them. N is the most important element of the physiological processes that govern the life of plants; as indispensable parts of the chlorophyll molecule, where important photosynthetic reactions for the production of biomass occur (Salisbury and Ross 1994). Nitrogen is taken up by plants primarily as ammonium and nitrate (Escobar 1990). In coffee agroforestry systems, they generally use leguminous species due to its high content of N and availability of absorption by crops (Giller and Wilson 1991). In coffee agroforestry system bacteria, play an important role in nitrogen transformation. The release of N is the term usually used to describe the loss of this element (in organic

and/or mineral form) from decomposing materials (Palm and Sánchez 1990). While N mineralization strictly refers to the transformation process of organic N in mineral N, a process that is important for the growth of the plants. The release of N is given by the difference between 100% of the N and the remaining N contained by the plant material.

Fassbender (1987) indicated that the percentage content of organic matter (OM) in the first layer of soil is high with respect to the subsequent layers. The values of the content of organic matter horizon in tropical soils vary by an average of 2% to 5%. The reduction of organic matter is notorious for the accumulation of organic residues and the activity of microorganisms in the first decimeters of the soil. On the other hand, it has direct and indirect effects on the availability of nutrients for plant growth and serves as a source of N, P, and S through mineralization by soil microorganisms and influences the contribution of nutrients from other sources, such as when required as an energy source for the bacterial attachment of N. Therefore, the amount of molecular N₂ fixed by free fixative will be influenced by the amount of energy available in the form of carbohydrate.

Furthermore, since the most widely accepted estimate of organic matter soil is based on the determination of organic carbon oxidizable (Method Walkley-Black; % MO=% CO₂ × 1,724), so the studies on the organic matter are studied organic carbon (Nair 1993).

The C:N ratio depends on the species and age of the same, and is a good indicator of susceptibility of litter to be degraded. The optimum range of organic residues is between 25:1 to 30:1; if the starting residue is rich in C and low in N, decomposition will be slow, but on the contrary, with high concentrations of N, it will be transformed into ammonia preventing proper biological activity. If the final material obtained after decomposition has a high C:N value (> 35), it indicates that it has not suffered a complete decomposition and if the index is very low (< 25), it can be by excessive mineralization, although it all depends on the characteristics of the starting material (Fassbender 1987; Oliver et al. 2002).

Vilas et al. (1993) found in Costa Rica that the release rate of N is similar and smaller, the loss of dry weight, excluding systems *Coffea arabica*+*E. poeppigiana*, which showed a release rate of N greater (60%) loss of dry weight with respect to the other systems tested (*Coffea arab-*

ica+*Cordia alliodora*, *Theobroma cacao*+*Erythrina poeppigiana* and *Theobroma cacao*+*Cordia alliodora*).

Teklay (2007) studied the decomposition of leaves of *Cordia africana* Lam. and *Albizia gummifera* G. F.Gmel, product pruning and used as green manure during the wet and dry Wondo Genet stations (Ethiopia). The experiment was carried out in two systems: agroforestry-shade coffee and adjacent agricultural land where corn is often used for cultivation. The species *C. africana* and *A. gummifera* are the dominant shade trees in the shade coffee system, providing between 63% and 72% of shade at 0.4 m above the ground. Litterbags that were buried in the two systems were recovered after 4, 8, 12, and 16 weeks, and nitrogen (N), phosphorus (P), potassium (K), cellulose, lignin, soluble polyphenols, and condensed tannin content were analyzed. The author expresses the N was immobilized during the first 8 weeks of the dry season. After 12 weeks of incubation, the loss of N in *A. gummifera* was higher during the dry season than during the wet season. N mineralization was also higher during the rainy season than during the dry season, in the shade coffee system than in farmland and between species. Moreover, the two species showed contrast patterns in the concentration of N in relation to the cumulative weight loss. In *A. gummifera*, N loss was proportional to the weight loss of the dry matter, while in *C. africana* weight loss of dry matter moved faster than N.

da Matos et al. (2011) report values of N release in legumes used as green manure in coffee agroforestry system in two farms in Minas Gerais, Brazil. They indicate that concentrations of N residues *Stizolobium aterrimum* were consistently higher than in the other residues on both farms, following the trend of losses of dry biomass, the values of decay rates for the release of N were 50.2% lower than in the *Araponga* farm in *Pedra Dourada* farm. At the end of 360 days, the released N corresponded to 78% of the initial content and 89% in both farms, respectively, indicating that a large part of N accumulated in plant tissue had been released in the early days of decomposition. The C/N ratio was between 15.1 and 18.6 in *Pedra Dourada* and between 13.0 and 24.2 in *Araponga*.

Farfan and Urrego (2007) presented Table 6 the results of their study of the decomposition of *Cordia alliodora*, *Pinus oocarpa*, and *Eucalyptus grandis* in coffee agroforestry systems in Colombia. It is observed that the final concen-

Table 6. Final concentrations of organic carbon (OC), nitrogen (N) and C: N ratio of coffee remaining material to free solar exposure and under shade and forest species *C. alliodora*, *P. oocarpa* and *E. grandis* in coffee agroforestry systems in Colombia (Adapted from Farfan and Urrego, 2007)

Species	OC%	N%	C:N
Coffee unshaded	49.5	2.5	19.8
Café with shade	50.1	3.0	16.9
<i>C. alliodora</i>	42.5	2.4	18.1
<i>P. oocarpa</i>	55.4	0.8	73.9
<i>E. grandis</i>	52.6	1.4	37.3

trations of nitrogen and organic carbon were higher in the shade coffee system. The species *C. alliodora* obtained the highest concentration of N and *P. oocarpa* had the highest concentration of organic carbon and the lowest concentration of N. As for the C:N ratio, it is observed that in the coffee alone and under shade is below 25, indicating that a complete decomposition process occurred in both systems. On the other hand, the C:N ratio in the shady species, only in *C. alliodora*, was completed the decomposition process.

Lignin, Polyphenols, Condensed Tannins, and Other Elements

Cellulose, hemicellulose, and lignin are the most important components of the litter, which constitute 50% to 80% of dry matter (Berg 2014). These macromolecules prior to assimilation by microorganisms must be hydrolyzed to simpler subunits, by extracellular enzymes.

After cellulose, lignin is the second most important component of litter. Lignin is a polymer consisting of phenylpropane units with multiple links and is degraded by an enzyme complex, including lignin peroxidases and tyrosinase, which act synergistically (Fioretto et al. 2005). The complexity of the molecular structure of lignin causes a delay in their degradation and their binding via covalent bonds to cellulose.

There are several studies that explain the role of lignin as a regulator of litter decomposition process (Tian et al. 1993). According to Tian et al. (1992) increasing lignin content decreases and the degree of decomposition can cause immobilization of nutrients, primarily nitrogen. This was also demonstrated by Melillo et al (1982).

Polyphenols are a heterogeneous group of natural sub-

stances characterized by a hydroxyl aromatic ring by one or more groups. These substances are compounds of different chemical secondary plant origin that occur in plant tissues (Harborne 1997). Total phenols disappear quickly from the leaves and have essentially disappeared out of the leaves in six weeks after fall. They have been reported rapid loss of soluble constituents of the leaves (Gallardo and Merino 1993) and polyphenols in various ecosystems (Rahman et al. 2017). However, the perception of phenols as inhibitors is too simple and different phenolic compounds can have many different functions within the litter layer and the underlying soil (Hättenschwiler and Vitousek 2000).

Some scientists hypothesize that polyphenols stimulate microbial activity and subsequently reduce plant-available N (Madritch and Hunter 2004). These results contribute important information to the growing body of evidence indicating that the quality of C moving from plants to soils is a critical component of plant-mediated effects on soil biogeochemistry and possibly competitive interactions among species (Rahman et al. 2017).

Tannins are phenolic substances that precipitate proteins and inhibit decomposition of organic matter. Tannins are defined as polymeric, water-soluble phenols that precipitate proteins. However, some soluble phenols that have similar structures and chemical properties to tannins do not precipitate proteins. The high presence of phenols does not indicate that the production of tannin is increased and that can lead to other components (Romero Lara et al. 2000).

Tannins are a heterogeneous group of phenolic compounds derived from flavonoids and gallic acid. Swain and Bate-Smith (1962) defined as soluble tannins water polyphenolic compounds with a molecular weight of 500 to 3000 Daltons that have the ability to precipitate alkaloids,

gelatine, and other proteins. The tannins found in higher plants are divided into two major classes termed proanthocyanidins or condensed tannins and hydrolyzable tannins (Rahman et al. 2017).

It is believed that tannins retard the rate of litter decay because they may form recalcitrant complexes with other substrates such as cellulose or protein (Horner et al. 1988). It is widely recognized that phenols have an important role in nutrient cycling and litter decomposition through their interactions with multilevel mineralization processes (Cornelissen et al. 1999; Hättenschwiler and Vitousek 2000). Apart from its toxicity to certain microorganisms, it is believed that the polyphenols, especially the fraction of tannins, affect the availability of nitrogen to plants during growth, primarily through the formation of complexes of organic nitrogen in the soil (Kraus et al. 2003). Tannins play an important role in the dynamics of nutrients, particularly for the N, and are critical to the activity of bacteria and soil fungi (Field and Lettinga 1992).

Tannins can also directly affect biogeochemical processes significantly in soils because they can form complexes and play a vital part in chemical reactions. Tannic acid can react rapidly with soil proteins related to soil quality (Halvorson et al. 2009). They also affect the processes of decomposition in the litter only during the first weeks of decomposition (Rahman et al. 2017). Mungia et al. (2004) studied the decomposition and release of nutrients from leaves of *Eucalyptus deglupta* and *Coffea arabica* and green leaves of *Erythrina poeppigiana*, single or in mixtures in two coffee farms in the Southern Zone of Costa Rica and result showed that decomposition of litter had a positive correlation with the content of homocelulosa and concentrations of P, N, and K, and negative relationship with the polyphenol content and lignin:N ratio (Table 6). The authors conclude that the concentration of polyphenols appears to limit the rates of decomposition of litter, while high concentrations of cellulose and hemicellulose, N, P, and K are positively correlated with high rates of decomposition. An example of this is that the litter *E. poeppigiana* decomposed and released nutrients at rates much higher than those of *E. deglupta* and *C. arabica*. However, K released very fast in all treatments including those contained litter *E. deglupta*. With the addition of *E. poeppigiana* leaves, the litter decomposition of *C. arabica* and *E. deglupta* and the release of K from the leaf lit-

ter of *E. deglupta* were accelerated.

Teklay (2007) conducted a research on decomposing leaves of *Cordia africana* and *Albizia gummifera*, a pruning product used as green manure during the wet and dry seasons in a shade coffee agroforestry system and agricultural land with maize crop. The result showed that lignin decomposition was significantly higher during the dry season in contrast to that found in the wet season, also among the systems studied (shade coffee system > farmland with corn). However, when the results were analyzed for each season, they showed that the significant effects of land use on the decomposition of lignin existed only during the wet season. On the other hand, an increase was observed both in absolute amounts and concentrations of lignin in the litter, as decomposition was executed. Polyphenols showed a high rate of decomposition and revealed differences between species that were affected by the season and land use systems. However, when these analyses were performed separately for each season, it was found that the effect of the decomposition of *A. gummifera*, loss of polyphenols is faster than that of *C. africana* but only during the wet season. Moreover, the loss of condensed tannins was significantly higher during the wet season than in the dry as well as among the species studied. The concentrations of condensed tannins showed exponential declines and increases in the litter (Teklay 2007).

Farfan and Urrego (2007) reported that there were no statistical differences in the release of phosphorus (P) in the litter of coffee in the four cropping systems. It was observed that *C. alliodora* transfers P at a higher rate than *P. oocarpa*, while immobilizing this nutrient in *E. grandis* occurs. The P release rates were higher in sunlight coffee and under shade eucalyptus than *C. alliodora* and *P. oocarpa*. No immobilization of potassium (K) in the coffee was recorded in one of its different cropping systems or forest species. The K release rates were equal in litter coffee (shade and free exposure) compared with those of *C. alliodora*. The values of K release rates of litter produced by *P. oocarpa* and *E. grandis* were equal, and in turn, they were different (lower) than those of coffee and *C. alliodora*. Furthermore, the highest rates of release of calcium (Ca) were recorded in the litter of *C. alliodora* and the coffee under the shade of eucalyptus. Despite not having registered immobilization of Ca in coffee or forest species, the lowest this nutrient release rates

were found in the litter of coffee under shade of *C. alliodora*, *P. oocarpa*, and *E. grandis*. Residues of coffee under the shade of *E. grandis* showed a higher rate of release of magnesium (Mg) than litter of coffee under the shade of *C. alliodora* and coffee at free sun exposure. Among forest species the lowest transfer rate was recorded in *E. grandis* when compared to *C. alliodora*; while there was *P. oocarpa* immobilization of this nutrient. The researchers conclude that over a period of 365 days of decomposition, the dry biomass produced by the ground coffee transferred 82.9% of P, 96.7% of K, 34.3% of Ca, and 63.1% of Mg. In the same way, *C. alliodora* transferred 54.4% of P, 93.6% of K, 54.0% of Ca, and 67.7% of Mg. For the same period, the leaf litter of *P. oocarpa* did not transfer P, Ca, and Mg to the soil, but there was 64.5% of K present in the residues. Also *E. grandis*, transferred 35.5% of P, 89.3% of K, 5.28% of Ca, and 39.9% of Mg.

Conclusion and Final Considerations

From the abovementioned discussion we conclude the following:

- The decomposition of leaf litter is key and limiting process in macro-nutrient cycles and models have been developed that predict the rate of decomposition and related to climatic, edaphic, residue, or even microbiological variables.
- The decomposition rate of litter can be affected by a number of factors, including the diversity of the type of litter in the environment. The effect of mixing different types of litter decomposition rates is increasingly being studied, but is still poorly understood.
- Shade trees protect the soil from heat stroke, help maintain organic matter, reduce evaporation, and maintain soil productivity, since they play an important role in controlling erosion, protecting soil against the impact of the rain; reduce runoff velocity by increasing surface roughness, water infiltration, and provide a layer of mulch so that tree roots create channels within the soil.
- It has been found that the green leaves of legumes generally provide a high amount of N to the soil, due to rapid decomposition and mineralization process that favors greater biomass for plants growing in association with legumes, such as coffee.
- There are few studies of decomposition made in coffee

agroforestry systems, for this reason, it is necessary to implement studies of decomposition and mineralization, and the microflora and fauna associated with these processes, so that serve as an important tool to develop models, enabling a description of the short, medium, and long-term dynamics of soil nutrients in coffee, because changes are laborious to measure and future levels of soil carbon can only be predicted using models.

- The information generated from research in coffee agroforestry systems have important operating implications, as it will decide the application of green manure from pruning trees associated with coffee cultivation, reducing the need for the application of fertilizers, and possibly rich soil microflora and fauna that get involved in the processes of decomposition and increase the availability of nutrients in the soil.

Acknowledgments

We would like to thank Mr. Chris Germain (SmileSonica Inc. Edmonton, Canada) and 2 anonymous referees for critical feedback and suggestions on the manuscripts.

References

- Aber JD, Melillo JM. 1991. Terrestrial Ecosystems. Saunders College Publishing, Philadelphia, pp. 200-205.
- Aber JD, Melillo JM, McLaugherty CA. 1990. Predicting long-term patterns of mass loss, nitrogen dynamics, and soil organic matter formation from initial fine litter chemistry in temperate forest ecosystems. *Can J Bot* 68: 2201-2208.
- Aerts R. 1997. Climate, leaf litter chemistry and leaf litter decomposition in terrestrial ecosystems: a triangular relationship. *Oikos* 79: 439-449.
- Aerts R, de Caluwe H. 1997. Initial litter respiration as indicator for long-term leaf litter decomposition of carex species. *Oikos* 80: 353-361.
- Anderson J, Flanagan P, Caswell E, Coleman D, Cuevas E, Freckman D, Jones J, Lavelle P, Vitousek P. 1989. Biological processes regulating organic matter dynamics in tropical soils. In: *Dynamics of Soil Organic Matter in Tropical Ecosystems*. (Coleman D, Malcolm J, Vehara G, eds). NIFTAL, University of Hawaii, Honolulu, pp 111-117.
- Aponte C, García LV, Marañón T. 2012. Tree species effect on litter decomposition and nutrient release in mediterranean oak forests changes over time. *Ecosystems* 15: 1204-1218.

- Arellano R, Paolini J, Vásquez L, Mora E. 2004. [Litter production and decomposition in three coffee agroecosystems in Trujillo State, Venezuela]. *Rev For Venez* 48: 7-14. Spanish.
- Baldwin IT, Schultz JC. 1984. Tannins lost from sugar maple (*Acer saccharum* Marsh) and yellow birch (*Betula allegheniensis* Britt.) leaf litter. *Soil Biol Biochem* 16: 421-422.
- Berg B. 2014. Foliar litter decomposition: a conceptual model with focus on pine (*Pinus*) litter--a genus with global distribution. *ISRN For* 2014: 838169.
- Berg B, Ekbohm G. 1991. Litter mass-loss rates and decomposition patterns in some needle and leaf litter types. Long-term decomposition in a Scots pine forest. VII. *Can J Bot* 69: 1449-1456.
- Berg B, Hannus K, Popoff T, Theander O. 1982. Changes in organic chemical components of needle litter during decomposition. Long-term decomposition in a Scots pine forest. I. *Can J Bot* 60: 1310-1319.
- Berg B, McLaugherty C. 2003. *Plant Litter: Decomposition, Humus Formation, Carbon Sequestration*. Springer-Verlag Berlin Heidelberg, Berlin, 286 pp.
- Berg B, McLaugherty C. 2014. *Plant litter: decomposition, humus formation, carbon sequestration*. Springer-Verlag, Berlin, pp 23.
- Bunell F, Tait DEN, Flanagan PW, Van Clever K. 1977. Microbial respiration and substrate weight loss-I: A general model of the influence of abiotic variables. *Soil Biol Biochem* 9:33-40.
- Cadisch G, Giller KE. 1997. *Driven by nature: Plant litter quality and decomposition*. CAB International, Wallingford, 409 pp.
- Cardona CDA, Sadeghian KHS. 2005. Cycle of nutrients and microbial activity in coffee plantations to free solar exposition and with shade of *Inga* spp. *Cenicafé* 56: 127-141.
- Coleman MD, Isebrands JG, Tolsted DN, Tolbert VR. 2004. Comparing soil carbon of short rotation poplar plantations with agricultural crops and woodlots in North Central United States. *Environ Manage* 33: 299-308.
- Cornelissen JHC, Pérez-Harguindeguy N, Díaz S, Grime JP, Marzano B, Cabido M, Vendramini F, Cerabolini B. 1999. Leaf structure and defence control litter decomposition rate across species and life forms in regional floras on two continents. *New Phytol* 143: 191-200.
- Corre MD, Dechert G, Veldkamp E. 2006. Soil nitrogen cycling following montane forest conversion in Central Sulawesi, Indonesia. *Soil Sci Soc Am J* 70: 359-366.
- Coûteaux MM, Bottner P, Anderson JM, Berg B, Bolger T, Casals P, Romanyà J, Thiéry JM, Vallejo VR. 2001. Decomposition of ¹³C-labelled standard plant material in a latitudinal transect of European coniferous forests: Differential impact of climate on the decomposition of soil organic matter compartments. *Biogeochemistry* 54: 147-170.
- da Matos ES, de Mendonça ES, Cardoso IM, de Lima PC, Freese D. 2011. Decomposition and nutrient release of leguminous plants in coffee agroforestry systems. *Rev Bras Cienc Solo* 35: 141-149.
- DaMatta F, Rodríguez N. 2007. Sustainable production of coffee in agroforestry systems in the Neotropics: an agronomic and ecophysiological approach. *Agron Colomb* 25: 113-123.
- Di Stefano JF, Fournier LA. 2005. Litterfall and decomposition rates of *Vochysia guatemalensis* leaves in a 10 year-old plantation, Tabarcia de Mora, Costa Rica. *Agron Costarricense* 29: 9-16.
- Díaz M. 2009. Production, decomposition of litterfall and shredder macroinvertebrates, in four agroecosystems of La Vieja river basin. MS thesis. Universidad Tecnológica de Pereira, Pereira, Colombia.
- Duarte EMG, Cardoso IM, Stijnen T, Mendonça MAFC, Coelho MS, Cantarutti RB, Kuyper TW, Villani EMA, Mendonça ES. 2013. Decomposition and nutrient release in leaves of Atlantic Rainforest tree species used in agroforestry systems. *Agrofor Syst* 87: 835-847.
- Dutta RK, Agrawal M. 2001. Litterfall, litter decomposition and nutrient release in five exotic plant species planted on coal mine spoils. *Pedobiologia* 45: 298-312.
- Escobar M. 1990. Nitrogen dynamics alley cropping poro (*Erythrina poeppigiana* (Walpers)) and Madero negro (*Gliricidia sepium* (Jacq)) with common bean (*Phaseolus vulgaris*). MS thesis. CATIE, Turrialba, Costa Rica, pp 98.
- Farfan VF. 2014. *Agroforestry and coffee agroforestry, Manizales, Caldas (Colombia)*. pp 342.
- Farfan VF, Urrego JB. 2007. Decomposition of leaf litter and nutrient release from *Coffea arabica* *Cordia alliodora* *Pinus oocarpa* and *Eucalyptus grandis* in agroforestry systems with coffee. *Cenicafé* 58: 20-39 (in Spanish with English abstract).
- Fassbender HW. 1987. Soil models of agroforestry systems, Turrialba. pp 491.
- Feng Y. 2009. K-model-a continuous model of soil organic carbon dynamics: theory. *Soil Sci* 174: 482-493.
- Field JA, Lettinga G. 1992. Toxicity of Tannic Compounds to Microorganisms. In: *Plant Polyphenols. Synthesis, Properties, Significance*. (Hemingway RW, Laks PE, eds). Plenum Press, New York, pp 673-692.
- Fioretto A, Di Nardo C, Papa S, Fuggi A. 2005. Lignin and cellulose degradation and nitrogen dynamics during decomposition of three leaf litter species in a Mediterranean ecosystem. *Soil Biol Biochem* 37: 1083-1091.
- Flanagan PW, van Cleve K. 1983. Nutrient cycling in relation to decomposition and organic-matter quality in taiga ecosystems. *Can J For Res* 13: 795-817.
- Flores P, Antonio D, Alvarez S, de Jesús O. 2006. Production, decomposition and release of nutrients from litter under coffee in full sun and with shade of *Gliricidia sepium* (Jacq) in Carazo, Nicaragua. Thesis. National Agrarian University, Nicaragua. pp 10-20. Spanish.
- Forney D, Rothman D. 2007. Decomposition of soil organic matter from physically derived decay rates. In: *AGU Fall Meeting*;

- San Francisco, CA; 2007.
- Gallardo A, Merino J. 1993. Leaf decomposition in two Mediterranean ecosystems of southwest Spain: Influence of substrate quality. *Ecology* 74: 152-161.
- Giller KE, Wilson KJ. 1991. Nitrogen Fixation in Tropical Cropping Systems. CAB International, Wallingford, UK, pp 167-237.
- Goma-Tchimbakala J, Bernhard-Reversat F. 2006. Comparison of litter dynamics in three plantations of an indigenous timber-tree species (*Terminalia superba*) and a natural tropical forest in Mayombe, Congo. *For Ecol Manag* 229: 304-313.
- Halvorson JJ, Gonzalez MJ, Hagerman AE, Smith JL. 2009. Sorption of tannin and related phenolic compounds and effects on soluble-N in soil. *Soil Biol Biochem* 41: 2002-2010.
- Handanyanto E, Cadisch G, Giller KE. 1994. Nitrogen release from prunings of legume hedgerow trees in relation to quality of the prunings and incubation method. *Plant and Soil* 160: 237-248.
- Harborne JB. 1997. Role of phenolic secondary metabolics in plants and their degradation in nature. In: *Driven by nature: plant litter quality and decomposition* (Cadisch G, Giller KE, eds). CAB International, Wallingford, pp 67-74.
- Harmon ME, Krankina ON, Sexton J. 2000. Decomposition vectors: a new approach to estimating woody detritus decomposition dynamics. *Can J For Res* 30: 76-84.
- Hartemink AE. 2005. Nutrient stocks, nutrient cycling, and soil changes in cocoa ecosystems: a review. *Adv Agron* 86: 227-253.
- Hättenschwiler S, Vitousek PM. 2000. The role of polyphenols in terrestrial ecosystem nutrient cycling. *Trends Ecol Evol* 15: 238-243.
- Hirobe M, Sabang J, Bhatta BK, Takeda H. 2004. Leaf-litter decomposition of 15 tree species in a lowland tropical rain forest in Sarawak: decomposition rates and initial litter chemistry. *J For Res* 9: 341-346.
- Hoorens B, Aerts R, Stroetenga M. 2003. Does initial litter chemistry explain litter mixture effects on decomposition? *Oecologia* 137: 578-586.
- Horner JD, Gosz JR, Cates RG. 1988. The role of carbon-based plant secondary metabolites in decomposition in terrestrial ecosystems. *Am Nat* 132: 869-883.
- Howard PJA, Howard DM. 1974. Microbial decomposition of tree and shrub leaf litter. 1. Weight loss and chemical composition of decomposing litter. *Oikos* 25: 341-352.
- Isaac ME, Gordon AM, Thevathasan N, Oppong SK, Quashie-Sam J. 2005. Temporal changes in soil carbon and nitrogen in west African multistrata agroforestry systems: a chronosequence of pools and fluxes. *Agrofor Syst* 65: 23-31.
- Jaramillo C. 2007. Shade coffee plants behavior and litter fall dynamics under agroforestry systems conditions. MS thesis. Universidade Federal de Viçosa, Avenida Peter Henry Rolfs, Brasil. pp 87.
- Jenny H, Gessel SP, Bingham FT. 1949. Comparative study of decomposition rates of organic matter in temperate and tropical regions. *Soil Sci* 68: 419-432.
- Kavvadias VA, Alifragis D, Tsioutsis A, Brofas G, Stamatelos G. 2001. Litterfall, litter accumulation and litter decomposition rates in four forest ecosystems in northern Greece. *For Ecol Manage* 144: 113-127.
- Kraus TEC, Yu Z, Preston CM, Dahlgren RA, Zasoski RJ. 2003. Linking chemical reactivity and protein precipitation to structural characteristics of foliar tannins. *J Chem Ecol* 29: 703-730.
- Kurz-Besson C, Coûteaux MM, Thiéry JM, Berg B, Remacle J. 2005. A comparison of litterbag and direct observation methods of Scots pine needle decomposition measurement. *Soil Biol Biochem* 37: 2315-2318.
- Lang GE. 1973. Litter accumulation through ecosystem development. Dissertation. Rutgers University, New Brunswick, New Jersey, USA.
- Lavelle P, Blanchart E, Martin A, Martin S, Spain A. 1993. A hierarchical model for decomposition in terrestrial ecosystems: application to soils of the humid tropics. *Biotropica* 25: 130-150.
- Lavelle P, Spain AV. 2005. *Soil Ecology*. Springer, Dordrecht, pp 404-423.
- López-Gutiérrez JC, Toro M, López-Hernández. 2001. Arbuscular mycorrhizae and enzymatic activity in the rhizosphere of *Trachypogon plumosus* Ness in three acid savanna soils. *Acta Biol Venez* 21: 49-57 (in Spanish with English abstract).
- Lousier JD, Parkinson D. 1976. Litter decomposition in a cool temperate deciduous forest. *Can J Bot* 54: 419-436.
- Madritch MD, Hunter MD. 2004. Phenotypic diversity and litter chemistry affect nutrient dynamics during litter decomposition in a two species mix. *Oikos* 105: 125-131.
- Melillo JM, Aber JD, Muratore JE. 1982. Nitrogen and lignin control of hardwood leaf litter decomposition dynamics. *Ecol* 63: 621-626.
- Montagnini FY, Jordan CE. 2002. Nutrient recycling. In: *Ecology and conservation of neotropical forest* (Guariguata MR, Kattan G, eds). Editorial tecnológica, Cartago, Costa Rica, pp 167-191.
- Moser G, Leuschner C, Hertel D, Hölscher D, Köhler M, Leitner D, Michalzik B, Prihastanti E, Tjitrosemito S, Schwendenmann L. 2010. Response of cocoa trees (*Theobroma cacao*) to a 13-month desiccation period in Sulawesi, Indonesia. *Agrofor Syst* 79: 171-187.
- Mungia R, Harmand M, Beer J, Hagggar J. 2004. Decomposition and nutrient release rates of *Eucalyptus deglupta* and *Coffea arabica* litter and *Erythrina poeppigiana* green leaves alone or mixed. *Agroforestería en las Américas* 41-42: 62-68.
- Nair PKR. 1993. An introduction to agroforestry. Kluwer Academic Publisher, Dordrecht, The Netherlands, pp 499.
- Nair PKR, Buresh RJ, Mugendi DN, Latt CR. 1999. Nutrient cycling in tropical agroforestry systems: myths and science. In: *Agroforestry in Sustainable Agricultural Systems* (Buck LE, Lassoie JP, Fernandes ECM, eds). CRC Press, Boca Raton, FL, pp 1-31.

- Oliver L, Pérez-Corona ME, Bermúdez de Castrol CF. 2002. Litter decomposition in oligotrophic Mediterranean grassland in the center of the Iberian Peninsula. *Anales de Biol* 24: 21-32.
- Olson JS. 1963. Energy storage and the balance of producers and decomposers in ecological systems. *Ecol* 44: 322-331.
- Pal D, Broadbent FE. 1975. Kinetics of rice straw decomposition in soils. *J Environ Qual* 4: 256-260.
- Palm CA, Sánchez PA. 1990. Decomposition and nutrient release patterns of the leaves of three tropical legumes. *Biotropica* 22: 330-338.
- Paul EA, Clark FE. 1996. Soil microbiology and biochemistry. Academic Press Inc., San Diego, USA, pp 340.
- Pereira AP, Graca MAS, Molles M. 1998. Leaf litter decomposition in relation to litter physico-chemical properties, fungal biomass, arthropod colonization, and geographical origin of plant species. *Pedobiologia* 42: 316-327.
- Petit-Aldana J, Uribe-Valle G, Casanova-Lugo F, Solorio-Sánchez J, Ramírez-Avilés L. 2012. Decomposition and nutrient release patterns of leaves of *Leucaena leucocephala* (Lam.) de Wit, *Guazuma ulmifolia* Lam. and *Moringa oleifera* Lam. in a mixed fodder bank. *Rev Chapingo Ser Cie* 18: 5-25.
- Rahman MM, Motiur MR. 2012. *Quantitative chemical defense traits, litter decomposition and forest ecosystem functioning*. In: Forest Ecosystems- More than Just Tree (Blanco JA, Lo YH, eds). InTech publication, EU, pp 295-314.
- Rahman MM, Petit-Aldana J, Tsukamoto J, Wu QS. 2017. Litter chemistry, decomposition and its effects on soil biogeochemistry of forest ecosystems. In: Forest Ecosystems: Management, Impact Assessment and Conservation (Elliott D, ed). Nova Publication, New York, USA, pp 21-44.
- Romero Lara CE, Palma Garcíay JM, López J. 2000. The influence of grazing on the concentration of total phenols and condensed tannins in *Gliricidia sepium* in the dry tropics. *Livest Res Rural Dev* 12: 39-50.
- Rovira P, Rovira R. 2010. Fitting litter decomposition datasets to mathematical curves: towards a generalised exponential approach. *Geoderma* 155: 329-343.
- Russo R, Budowsky G. 1986. Effect of pollarding frequency on biomass of *Erythrina poeppigiana* as a coffee shade tree. *Agrofor Syst* 4:145-162.
- Salinas N, Malhi Y, Meir P, Silman M, Roman Cuesta R, Huaman J, Salinas D, Huaman V, Gibaja A, Mamani M, Farfan F. 2011. The sensitivity of tropical leaf litter decomposition to temperature: results from a large-scale leaf translocation experiment along an elevation gradient in Peruvian forests. *New Phytol* 189: 967-977.
- Salisbury FB, Ross CW. 1994. Fisiología vegetal. 4th ed. Grupo Editorial Iberoamérica, México, pp 759.
- Siebert SF. 2002. From shade- to sun-grown perennial crops in Sulawesi, Indonesia: implications for biodiversity conservation and soil fertility. *Biodivers Conserv* 11: 1889-1902.
- Singh JS, Gupta SR. 1977. Plant decomposition and soil respiration in terrestrial ecosystems. *Bot Rev* 43: 449-528.
- Slade EM, Riutta T. 2012. Interacting effects of leaf litter species and macrofauna on decomposition in different litter environments. *Basic Appl Ecol* 13: 423-431.
- Staver C, Guharay F, Monterroso D, Muschler RG. 2001. Designing pest-suppressive multistrata perennial crop systems: shade-grown coffee in Central America. *Agrofor Syst* 53: 151-170.
- Swain T, Bate-Smith EC. 1962. Flavonoid Compounds. In: Comparative Biochemistry (Florkin M, Mason HS, eds). Academic Press, New York. pp 755-809.
- Swift MJ, Anderson JM. 1989. Decomposition. In: Tropical rain forest ecosystems: biogeographical and ecological studies (Lieth H, Werger MJA, eds). Elsevier Science, New York, pp 547-569.
- Swift MJ, Anderson JM, Heal OW. 1979. Decomposition in terrestrial ecosystems. University of California Press, San Francisco, USA, pp 371.
- Teklay T. 2007. Decomposition and nutrient release from pruning residues of two indigenous agroforestry species during the wet and dry seasons. *Nutr Cycl Agroecosyst* 77: 115-126.
- Teklay T, Malmer A. 2004. Decomposition of leaves from two indigenous trees of contrasting qualities under shaded-coffee and agricultural land-uses during the dry season at Wondo Genet, Ethiopia. *Soil Biol Biochem* 36: 777-786.
- Tenney FG, Waksman SA. 1929. Composition of natural organic materials and their decomposition in the soil. 4. The nature and rapidity of decomposition of the various organic complexes in different plant materials, under aerobic conditions. *Soil Sci* 28: 55.
- Tian G, Brussaard L, Kang BT. 1993. Biological effects of plant residues with contrasting chemical compositions under humid tropical conditions: effects on soil fauna. *Soil Biol Biochem* 25: 731-737.
- Tian G, Kang BT, Brussaard L. 1992. Effects of chemical composition on N, Ca, and Mg release during incubation of leaves from selected agroforestry and fallow plant species. *Biogeochem* 16: 103-119.
- Tietema A, Wessel WW. 1994. Microbial activity and leaching during initial oak leaf litter decomposition. *Biol Fertil Soil* 18: 49-54.
- Van Cleve K. 1971. Energy- and weight-loss functions for decomposing foliage in birch and aspen forests in interior Alaska. *Ecology* 52: 720-723.
- Vilas BO, Imbach AC, Mazzarino MJ, Bonnemann A, Beer J. 1993. Litter decomposition in agroforestry systems of *Cordia* and *Erythrina* en Turrialba, Costa Rica. In: Congreso Forestal Español 1993; Pontevedra, Spain; pp 343-350.
- Villavicencio-Enríquez L. 2012. Production, weight loss and decomposition rates of leaf litter in traditional and rustic coffee systems and medium tropical forest in Veracruz, Mexico. *Rev Chapingo Ser Cie* 18: 159-173.

- Wang Q, Wang S, Huang Y. 2008. Comparisons of litterfall, litter decomposition and nutrient return in a monoculture *Cunninghamia lanceolata* and a mixed stand in southern China. For Ecol Manag 255: 1210-1218.
- Wardle DA, Bonner KI, Nicholson KS. 1997. Biodiversity and plant litter: experimental evidence which does not support the view that enhanced species richness improves ecosystem function. Oikos 79: 247-258.
- Weerakkody J, Parkinson D. 2006a. Input, accumulation and turnover of organic matter, nitrogen and phosphorus in surface organic layers of an upper montane rainforest in Sri Lanka. Pedobiologia 50: 377-383.
- Weerakkody J, Parkinson D. 2006b. Leaf litter decomposition in an upper montane rainforest in Sri Lanka. Pedobiologia 50: 387-395.
- Wieder RK, Lang GE. 1982. A critique of the analytical methods used in examining decomposition data. Ecology 63: 1636-1642.
- Wilson JO, Buchsbaum R, Valiela I, Swain T. 1986. Decomposition in salt marsh ecosystems: phenolic dynamics during decay of litter of *Spartina alterniflora*. Mar Ecol Prog Ser 29: 177-187.
- Woodwell GM, Marples TG. 1968. The influence of chronic gamma irradiation on the production and decay of litter and humus in an oak-pine forest. Ecol 49: 456-465.
- Xuluc-Tolosa FJ, Vester HFM, Ramírez-Marcial N, Castellanos-Albores J, Lawrence D. 2003. Leaf litter decomposition of tree species in three successional phases of tropical dry secondary forest in Campeche, Mexico. For Ecol Manag 174: 401-412.