Litter inputs and standing stocks in riparian zones and streams of the Brazilian Atlantic Forest under cocoa agroforestry

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Abstract

Background. Cocoa is an important tropical tree crop that is mainly cultivated in agroforestry systems (AFS). This system, also known as *cabruca* in northeastern Brazil, holds promise to reconcile biodiversity conservation and economic development. However, since cocoa AFS alters forest structure composition, it can affect litter dynamics in riparian zones and streams, although the degree of such impacts is poorly known, because pertinent studies in cocoa AFSs are rare. Thus, our objective was to determine litter inputs and standing stocks in riparian zones and streams under three types of forest: managed cocoa AFS, abandoned cocoa AFS, and secondary forest.

Methods. We determined terrestrial litter fall (TI), vertical (VI) and lateral (LI) litter inputs to streams, and litter standing stocks on streambeds (BS) in the Atlantic Forest of northeastern Brazil. Litter was collected every 30 days from August 2018 to July 2019 using custom-made traps. The litter was dried, separated into four fractions (leaves, branches, reproductive organs, and miscellaneous material) and weighed.

Results. Terrestrial litter fall was similar for the secondary forest (SF), abandoned AFS (AC), and managed AFS (MC), following the order AC>SF>MC. Despite differences in the amounts of litter inputs and standing stocks among the forests, seasonal patterns in the abandoned AFS (AC) were more similar to those of the secondary forest (SF) than the managed AFS, suggesting potential of abandoned AFS to restore litter dynamics resembling those of secondary forests.

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Introduction

Riparian zones are important for the functioning of headwater streams (Vannote et al., 1980; Naiman, Décamps & McClain et al., 2005), including in tropical zones (Gonçalves Júnior et al., 2014, Bambi et al., 2016, Rezende et al., 2017a; Rezende et al., 2019, Calderón et al., 2019). The riparian canopy limits instream primary production and provides allochthonous organic matter to stream and riparian food webs in the form of litter, which increases heterotrophic metabolism (Gonçalves Júnior et al., 2014, Rezende et al., 2019). Therefore, litter dynamics are a fundamental characteristic of headwater streams (Abelho & Graça, 1996; Neres-Lima et al., 2017). In the tropics, litter is typically supplied throughout the year (Tonin et al. 2017), although this pattern varies among forest types (Lindman et al. 2017, Seena et al. 2017), largely driven by precipitation and temperature regimes (REF). Changes in the structure and composition of riparian forests can affect the supply of litter to streams and their riparian zones (Delong & Brusven,1994; Ferreira et al., 2019; Wild, Gücker & Brauns, 2019), as well as instream litter dynamics (Stufin, Wohl & Dwire, 2016; Tiegs et al., 2019).

Many tropical forests are jeopardized by rapid deforestation and expansion of agriculture (REF). This includes the Atlantic Forest of Brazil as one of the most threatened tropical forests worldwide (Winbourne et al., 2018, Taubert et al., 2018; Bawa et al., 2004). Agroforestry systems (AFSs), however, have potential to partly reconcile the conservation of tropical forest patches with economic development (Cassano et al., 2009; Schroth et al., 2011). One example is the cultivation of cocoa in the Atlantic Forest of northeast Brazil where cocoa trees (*Theobroma cacao* L.) are grown in AFS that cover a large portion of the remnant Atlantic Forest (Piasentin et al., 2014). The cocoa trees are planted in the shade of native forest trees (dominant and codominant strata) and are surrounded by natural vegetation. Therefore, cocoa AFS are

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Studies involving litter dynamics in riparian zones of productive tropical systems are scarce. These studies could shed valuable light on the effects of anthropogenic changes on carbon cycling and climate change (Wright, 2005; Boyero et al., 2011; Stufin, Wohl & Dwire, 2016) and aquatic biota and ecological processes in streams (Ferreira et al. 2019). Spatial and temporal patterns of litter dynamics in different riparian zones of tropical environments are driven by precipitation and temperature due to the control of litter production. Furthermore, these forests have an even supply of litter throughout the year (Tonin et al. 2017) although these patterns may vary in different phytophysiognomies (Lindman et al. 2017, Seena et al. 2017).

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Studies on litter dynamics in tropical streams and their riparian zones are scarce, especially under cocoa AFS, although some evidence suggests that replacing cocoa AFS changes the cycling of carbon and nitrogen in streams (Costa et al., 2017; Souza et al., 2017; Costa et al., 2018), possibly as a result of altered litter supply by riparian vegetation. Thus, the current study aimed to assess the influence of cocoa AFS on litter dynamics by determining differences in secondary forest and managed and abandoned AFS on litter inputs and benthic standing stocks in streams and riparian zones in these forests. We expected that i) managed and abandoned cocoa AFS produce more litter than tropical secondary forests due to differences in forest structure (Fontes et al., 2014; Seena et al., 2017); ii) streams running through those AFS tend to receive larger amounts of litter (França et al., 2009; Gonçalves Júnior et al., 2014), resulting in greater litter standings stocks in the streambeds (Webster et al., 1994; Lisboa et al., 2015); and iii) tropical riparian forests are driven by precipitation due to the control of water availability on litter production (Tonin et al., 2017).

Methods

Study area

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The study was conducted in the riparian zones of three small watersheds (Fig. 1) representing secondary forest (E 485415, N 8397615), abandoned cocoa AFS (E 481551, N 8364478), and managed cocoa AFS (E 448466, N 8363187). All sites are located in the Atlantic Forest of southern Bahia in northeast Brazil. The Climate is wet tropical (hot and humid with no defined dry season, Af according to the Köppen classification) with annual rainfall ranging from 1100 to 2200 mm. The study streams are second-order according to the Strahler classification. Daily rainfall data were obtained from the website of the Real-Time Climate Monitoring Program of the Northeast Region (PROCLIMA; http://proclima.cptec.inpe.br) for the municipalities of Itacaré, Ilhéus, and Barro Preto (Fig. 2).

The secondary forest, which covers XY ha, is located in a conservation area, Serra do Conduru State Park (License 2017-013654/TEC/PESQ-0014). The vegetation is a mosaic of different developmental stages, including secondary forest. The uniform canopy of the forest exceeds 25 m in height and includes a few emerging individual trees, epiphytes, large vines, and a dense understory (Martini et al., 2007; Costa et al., 2018). Tree species density levels in the area were high at all sites, independent of forest successional stage (Martini et al., 2007). Old growth forest totaled 144 species, old logged forest had XY species, and recently logged forest 134. Of the 142 species sampled in the Serra do Conduru State Park, 51.4% are endemic to the Atlantic Forest.

The abandoned AFS covers 73.4 ha and is located in an AFS (Santa Cruz) where crop management was abandoned 20 years before the present study. The watershed has a slope of around 5%. Old cocoa trees and other, irregularly distributed species such as jackfruit, erythrina, embaúba, and jequitibá trees (Argôlo, 2009) resulted in a medium level of shading (70%). The managed AFS is located in another AFS (Nova Harmonia) with a total area of 89.8 ha. It comprises areas under cocoa production, a forest patch in the central portion, and two areas undergoing regeneration (Santos et al., 2016). Management consists of pruning cocoa trees every six months with the biomass left in place, vegetation cutting, and some liming for soil amelioration. The cocoa plants were spaced at 3x3m and intercropped with introduced shade trees (erythrina).

Litter inputs and benthic standing stocks

Litter inputs and benthic standing stocks were determined from August 2018 to July 2019. The methodology has been presented in França et al. (2009), Gonçalves Júnior et al. (2014), Bambi et al. (2016) and Tonin et al. (2017). Terrestrial litter fall (TI), vertical

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Deleted: In the present study, litter input and stock were measured monthly at each study site for one year, from August 2018 to July 2019. To understand litter dynamics, the samples were collected in different compartments in a 100 m stretch in each riparian zone, 20 m away from one another. Figure 3 shows the sample design adopted for each collection point. The compartments were used to assess t…erresti ...

(VI) and lateral (LI) litter inputs to streams, and litter deposited on the streambeds (benthic standing stock) were assessed along 100 m stream stretches at each location (Figure 3).

TI deposited on the riparian soil represents the amount of litter that can potentially be transported to the stream. It was collected with 10 nets (1 mm mesh, 2.5 m² total area), five on both sides of the streams, installed 1 m above the ground at 20 m distance from one another in the riparian zone. VI represents litter that falls directly into the streams from the riparian canopy. It was collected with 27 buckets (30 cm diameter, 1.9 m² total area) installed perpendicular to the stream, 2 m above the water surface. The buckets were arranged in three groups of nine, spaced approximately 30 m apart with a distance of 1 m between the individual buckets. Small holes in the bottom of the buckets allowed any collected water to drain. LI represents the indirect input of litter by lateral movement from the forest floor to the stream due to gravity, runoff, wind, or animal action. LI was collected with 10 nets (1 mm mesh, 1.5 m² total area) arranged at ground level at the stream margins, five on both sides of the streams. Total litter input to the streams was calculated as the sum of lateral and vertical inputs. Finally, benthic standing stocks represent the litter accumulated on the streambed. It was estimated by taking Surber samples (0.25 mm mesh, 0.45 m² total area), five in each stream at 20 m distance from one another (Fig. 3).

The litter trapped in the nets and buckets was collected at monthly intervals and sorted into four fractions upon return to the laboratory: leaves, branches (i.e. woody pieces less than 25 cm), reproductive organs such as flowers and fruits, and miscellaneous material (i.e. unidentified plant matter and animal remains). The sorted litter was dried in an oven at 60 °C for 72 hours and weighed. TI, VI and LI were expressed in g dry mass m^{-2} d^{-1} and BS in g dry mass m^{-2}. LI per m^2 was calculated by dividing the collected litter mass by the trap width and multiplying the result by two (to account for inputs from both stream banks) and by the mean channel width (Elosegi & Pozo, 2005; Pozo et al., 2009). The annual litter inputs to the streams and riparian zones corresponds to the sum of the mean monthly litter inputs during the study year (Table 1).

Statistical analysis

Differences in litter inputs and benthic standing stocks among the forests were assessed by comparing bootstrapped 95% confidence intervals, which were computed by the bias-corrected and accelerated (BCa) method with boot function and package, based on

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1,000 bootstrap replicates (Davison & Hinkley, 1997; Canty & Ripley, 2016). Differences were considered significant when the confidence intervals did not overlap. Bootstrapping is robust against violations of assumptions underlying parametric tests, such as normal distribution of the residuals and homogeneity of variances (Efron & Tibshirani 1993; Johnson, 2001), which were observed for the litter input and standing stock data.

Generalized additive mixed models (GAMM) were used to explore the seasonal patterns in litter inputs and standing stocks of the four collected litter fractions (Tonin et al., 2017; 2019), as a predictor in a normal distribution (identity-link function),… Sites, traps and time were used as random components of the GAMM models. The amount of smoothing in an additive model is expressed as effective degrees of freedom (edf). The higher an edf value, the lower the linearity on a curve and variation over time, with an edf of 1 indicating a perfectly linear effect. The additive mixed models were fitted using the 'by' command in the 'mgcv' package in R. Validation was used to estimate the optimal amount of smoothing (Wood, 2017). The residual spread within models among sampling dates was measured by using the varIdent function in R. Additional analytical protocols, details of residual tests, and model validation approaches are available in Zuur et al. (2009).

Results

Leaf material was the single largest litter fraction, with percentages ≥60% for TI and VI and ≥70% for LI in the secondary forest and abandoned AFS (Fig. 4, Table 1). In the managed AFS, the percentages of TI, VI, and LI were 56, 41, and 62%, respectively. Leaves also represented large portions of the instream standing stock of litter, 61% in the abandoned AFS, 57% in the managed AFS, and 38% in the secondary forest. Miscellaneous types of organic matter was the second most abundant litter fraction, with the highest percentages observed in secondary forest and abandoned AFS (43% and 22%, respectively). Branches accounted for the highest percentages of litter standing stocks (secondary forest 19%, abandoned AFS 16%) and TI (secondary forest 9%, abandoned AFS 12%) (Table 1). Because of their sporadic and transient occurrence, reproductive parts accounted for low proportions of the total litter, although this fraction was larger in managed AFS (Table 1). Managed AFS also exhibited a higher contribution of reproductive plant parts in all types of litter inputs and standing stocks (Fig. 4). Branches and miscellaneous litter, were generally similar in all forest,

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except for higher benthic standing stocks of miscellaneous litter in the secondary forest compared to managed and abandoned AFSs (Fig. 4).

The greatest seasonal variation was found for leaves, with the highest contributions during the rainy season (Fig. 5). Seasonal variation was less pronounced and generally not significant for branches, reproductive plant parts, and miscellaneous litter (Figs S1 to S3). Vertical litter inputs showed seasonal patterns for leaves in the secondary forest (effective degrees of freedom – edf = 5.5; Fig. 5a) and abandoned AFS (edf = 5.1; Fig. 5b), with higher contributions during the rainy months, from November to February, in both forests. Vertical leaf inputs in the managed AFS decreased linearly over time, as reflected by an edf value close to 1 (Fig. 5c). Terrestrial leaf inputs showed a sinusoidal pattern is the secondary forest and managed AFS, which was reflected by high edf values of XY and XY, respectively. A peak in the rainiest months was observed in all three forests but the second peak was missing in the abandoned AFS. The largest lateral inputs of leaves were observed from January to March (edf = 1.9; Fig. 5) in the period of least rainfall (Fig. 2). Standing stocks of leaf litter showed different trends than leaf litter inputs. The sine wave shifted to the right, indicating that leaf input occurred just after the rainiest periods (Fig. 5).

Total annual litter fall in the riparian zone of the abandoned AFS, managed AFS, and secondary forest was 181, 122, and 118 g dry mass m^{-2}, respectively. In the abandoned and managed AFS, 56% of the litter was deposited on the forest floor (TI) while 44% was directly deposited in the streams (VI). In the secondary forest, the percentages of TI and VI were 63% and 37%, respectively. In the managed AFS, 66% of the litter fall in the riparian zone entered the streams by lateral movement. The respective contribution in the abandoned AFS was only 16% and 37% in the secondary forest. The average annual total litter standing stock in the managed AFS was more than two times lower than in the abandoned AFS and more than three times lower than in the secondary forest (Fig. 6).

Discussion

The results indicate that (i) production (terrestrial inputs) was similar for the secondary forest (SF), abandoned AFS (AC), and managed AFS (MC), following the order AC>SF>MC; (ii) litterfall to the stream (vertical input) and terrestrial inputs were

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higher in the abandoned AFS (higher leaf input); (iii) lateral input was higher in the managed AFS than in the other areas (except for branch); (iv) and total benthic stock was higher in the secondary forest than in the abandoned and managed AFS.

Although both AFS were expected to produce more litter (Dawoe, Isaac & Quashie-Sam, 2010; Fontes et al., 2014) than the secondary forest, the abandoned AFS was the most productive area and its streams received greater vertical litter input than the managed AFS and the secondary forest. High production in the abandoned AFS may be explained by the phytophysiognomy of riparian vegetation (Gonçalves et al., 2014; Rezende et al., 2017a) and successional stages of plant community recovery (Sambuichi & Haridasan, 2007; Rolim et al., 2017). High production in the abandoned AFS may be caused by factors such as abundant deposits of biomass from crops (Beer et al., 1998), which is influenced by the consequent increase in carbon stock in the soil, when compared to the other areas (Gama-Rodrigues et al., 2010; Costa et al., 2018), and the rapid dynamics of nutrient cycling in these systems (Nair et al., 1999).

Previous studies have reported that litter input to streams depends on litter production in the areas (França et al., 2009; Gonçalves Júnior et al., 2014). In general, changes in litter dynamics are primarily caused by the absence of natural riparian zones, which were traditionally replaced by the cultivation system itself for cocoa plantations along the stream banks (Piasentin et al., 2014). Riparian zones with natural vegetation are important for the structural and functional integrity of streams (Gonçalves Junior et al., 2014, Rezende et al., 2017b). Moreover, the results highlight that tree configuration of the AFS had ecological implications for the functioning of streams in the AFS on the amount of litter by input and stock.

The abandoned AFS exhibited a similar pattern to the secondary forest in terms of balanced low total litter input compared to the intensively managed AFS. Riparian

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vegetation near the streams is usually preserved (Ferreira et al., 2019). In the abandoned AFS, this vegetation is present and is, therefore, similar to the secondary forest rather than the managed AFS, which does not have this riparian zone. Intensive management may promote loss of plant species in the managed AFS due to the replacement of native shade tree species with high commercial value (Cassano et al., 2009, Piasentin Saito & Sambuichi, 2014).

Other factors that could be linked to the higher production of litter in the abandoned AFS are justified by Gama-Rodrigues et al. (2010), who showed that production is directly related to the age of vegetation, which is greater in older areas. Abandoned AFSs tend to be favorable environments for forest regeneration and provide more shade than managed AFSs (Rolim et al., 2017). Moreover, the leaf surface may increase in more shaded areas due to lower rates of photosynthesis caused by lower amounts of solar radiation (Beer et al., 1998). These factors tend to increase biomass contribution due to the increased leaf surface since leaves are the main component of this litter (Gonçalves Junior et al., 2014; Bambi et al., 2016; Tonin et al., 2017).

The higher production of litter in the abandoned AFS is corroborated by spatial and seasonal patterns in this area. The litter input and stock in the abandoned AFS were closer to the secondary forest than the managed AFS. Therefore, abandoned AFSs with low management may have highly favorable conditions for the regeneration of tropical forests (Rolim et al., 2017) and can be used as strategic conservation areas for tropical forest remnants in riparian zones of the Atlantic Forest (Faria et al., 2007; Cassano et al., 2009; Scroth et al., 2011; Sambuich et al., 2012). The presence of pioneer species could explain this regeneration process due to the ecological succession process (Rolim & Chiarello 2004, Sambuichi & Haridasan 2007, Sambuichi et al. 2012).

The tendency toward increased lateral contribution in the managed AFS may be caused by crop management, which involves hoeing and soil cleaning (Sambuichi et al., 2012; Mello & Gross, 2013) and can facilitate leaching and transport of detritus along the side of the stream through runoff (Afonso, Henry & Rodella, 2000; Wantzen et al., 2008). In cocoa AFS areas, intensive management affects the structure and composition of vegetation (Deheuvels et al., 2014). Furthermore, some management practices are related to the introduction of exotic species necessary for cultivation (Sambuichi, 2002; Piasentin, Saito & Sambuichi, 2014; Rolim et al., 2017) and the thinning of vegetation to obtain the desired shade levels for production (Johns, 1999). Another possible factor associated with the increased lateral contribution in the managed AFS is the morphology of the margins of this stream related to the topographic structure of the area, such as margin slope, soil characteristics, and runoff, all of which are closely related and favor lateral input to streams (Wantzen et al., 2008; Lisboa et al., 2015). The managed AFS also had the highest contribution of reproductive plant parts. This behavior may be explained by the management and phenology of shade species used in cocoa cultivation (Piasentin, Saito & Sambuichi, 2014; Rolim et al., 2017). The high contribution of reproductive matter in the managed AFS is caused by the presence of exotic species (e.g. *Artocarpus heterophyllus*, *Spondias mombin*, and, particularly in this study, *Clitoria fairchildiana*) with different phenological patterns than native riparian forests (Sambuichi & Haridasan, 2007; Sambuichi et al., 2012). The reproductive parts are transitory resources when compared to fractions such as leaf and branch (Elosegi & Pozo, 2005), while the high input of flowers and fruits in the tropical streams may imply an accelerated decomposition due to a higher nutritional quality than leaves (Rezende et al., 2019).

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The smaller lateral contributions found in the secondary forest and the abandoned AFS may be related to the greater density of trees and physical heterogeneity of the stream margins (Naiman, Décamps & McClain et al., 2005). Moreover, higher biomass of roots and fallen tree trunks in these forests with lower anthropogenic impacts (secondary forest and abandoned AFS) tends to favor litter retention in the riparian zone. The complex root system of riparian vegetation also reduces runoff (Tank et al., 2010) by minimizing the transport of litter to streams. The greater presence of root biomass and large fallen trunks is more common in areas with a low anthropogenic effect, such as the secondary forests and abandoned AFSs. In the managed AFS, regular shade tree cutting, and selective weeding prevented the loss of cocoa trees due to the fall of decomposing fragments from the shade trees (Johns, 1999; Piasentin, Saito & Sambuichi, 2014).

Benthic stock reflects ecosystem functioning, especially retention, transport, decomposition, respiration, and consequent stability in the energy balance of the ecosystem (Elosegi & Pozo, 2005; Tank et al., 2010). High benthic stock in secondary forests suggests that the stock is not only goverend inputs (França et al., 2009; Lisboa et al., 2015; Bambi et al., 2016) but may alos be related to slow decomposition and downstream transport (Gonçalves Júnior et al., 2014; Rezende et al., 2017a). The high amount of miscellaneous matter in the secondary forest stream reveals the level of processing of stored litter and can represent the degree of decomposition. In small order streams, litter retention in the system favors processing into smaller fractions in the headwater streams instead of litter being transported downstream in the form of coarse particles (Bilby & Likens, 1980).

In contrast, the predominant cocoa leaves in the benthic stock of cocoa AFS vegetation tend to be the potential energy source for primary production of the aquatic ecosystems of these areas. High concentrations of lignin and cellulose in cocoa leaves slows litter

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Deleted: Once litter starts to decompose, it is broken down and turned into simple molecules by the action of physical, chemical, and biological factors (Farjalla, Marinho & Esteves, 1999; Rezende et al. 2019).

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decomposition in the soil of cocoa AFS (Dawoe, Isaac & Quashie-Sam, 2010), which is likely the case also in streams (Tank et al., 2010; Lemes da Silva et al., 2017). In the managed AFS, the high contribution of reproductive matter favored the high benthic standing stock in this forest. Moreover, this litter fraction was small or absent in the secondary forest and abandoned AFS.

Litter inputs and standing stocks in the abandoned AFS were closer to those in the secondary forest than the managed cocoa AFS. Therefore, abandoned AFSs with poor management can provide favorable conditions for the dynamics of litter, as found in more preserved riparian zones. Abandoned AFSs have a high capacity to regenerate the richness of tree species after abandonment (Sambuichi & Haridasan, 2007) due to the absence of management activities, such as litter removal and soil cleaning. The remaining and surrounding forest functions as a seed source, which favors forest recovery in abandoned AFSs (Rolim et al., 2017). The results highlight that the configuration of vegetation in the AFS has ecological implications for the amount of litter inputs and benthic stocks. The absence of management minimizes selective pressure on species during natural regeneration in abandoned AFS areas (Rolim et al., 2017), which may be one of the reasons for the similar input and stock litter in the secondary forest. Thus, the expression of the phenology of species is the main factor for the dynamics of litter in these riparian zones since they exclude the effect of management in these areas. More intensive anthropogenic management may alter the structure of riparian plant communities and affect ecosystem functioning over time (Delong & Brusven, 1994; Ferreira et al. 2018).

Acknowledgements

We are grateful to Mr. Hermann Rehem, owner of Nova Harmonia farm for granting us the license to collect data on his farm. We appreciate the support and partnership of the

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Our results highlighted that, although the secondary forest and AFSs were similar in terms of production, litterfall to streams in the AFSs (abandoned and managed) was higher than in the secondary forest. Moreover, we consider that, although the management of these areas can alter vegetation cover, ecological processes such as litter dynamics can make these areas closely resemble secondary forests. The high similarity of the secondary forest with the abandoned AFS in terms of litter input and stock demonstrated the potential of the abandoned AFS to provide favorable conditions for the restoration of ecological processes such as litter dynamics. However, future investigations on the concentration of nutrients are necessary to further elucidate the nutritional quality of this litter and whether it varies according to the composition and structure of vegetation in these areas. ¶
¶

Aquariparia research group at the Universidade de Brasilia - UnB. We also thank to Cipriana Leme for the English revision of this manuscript.

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Comment [MOG58]: Many reference have probably been deleted by editing the text.

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