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BENEFÍCIOS AMBIENTAIS DO SISTEMA DE CULTIVO EM ALEIAS NA EFICIÊNCIA DO USO DE NUTRIENTES, COM VISTAS À PRODUÇÃO DE SILAGEM NA PRÉ-AMAZÔNIA MARANHENSE

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Tese apresentada ao Programa de Pós-Graduação em Biodiversidade e Biotecnologia da Rede BIONORTE, na Universidade Federal do Maranhão, como requisito para a obtenção do Título de Doutor em Biodiversidade e Biotecnologia

Orientadora: Profª. Drª. Alana das Chagas Ferreira Aguiar

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SÃO LUIS – MA
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Portela, Larissa Brandão. Benefícios ambientais do sistema de cultivo em aleias na eficiência do uso de nutrientes, com vistas à produção de silagem na pré-amazônia maranhense. 2018. 150 f. Tese (doutorado BIONORTE) - Universidade Federal do Amazonas. Maranhão, São Luis, 2018.

RESUMO

No Brasil, o cultivo em aleias está se tornando uma prática agroflorestal aceitável em algumas regiões. Para entender melhor seu potencial de proporcionar benefícios ambientais aliado ao aumento da produtividade, a pesquisa envolvendo sistemas em aleias expandiu-se significativamente nas últimas décadas. Com o objetivo de proporcionar o aprimoramento nos índices de produtividade e sustentabilidade dos pequenos agricultores da região da Amazônia maranhense, foi utilizado um sistema em aleias para a produção de milho destinado à produção de silagem. Foi instalado, nos anos de 2015, 2016 e 2017 sob sistema de cultivo em aleias, um experimento em blocos ao acaso, com parcelas de 10 x 4 m^2 e quatro repetições, para avaliar o crescimento e a produtividade do milho híbrido (AG1050) e *QPM* (BR743), utilizando três espécies de leguminosas arbóreas, *Leucaena leucocephala, Gliricidia sepium e Acacia mangium*. Foram avaliados a eficiência do uso do nitrogênio, a eficiência de recuperação do nitrogênio, a produtividade do milho, produtividade de silagem de milho, o potencial de estoque de carbono, a decomposição e liberação dos nutrientes presentes na biomassa das leguminosas e na serapilheira do sistema, o levantamento de ervas daninhas e os benefícios econômicos com a finalidade aprimorar o cultivo de milho destinado à silagem na Amazônia maranhense sob sistema em aleias.

Palavras chave: alimentação animal, sistema agroflorestal, leguminosas arbóreas.

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*Adviser: Alana das Chagas Ferreira Aguiar, D.Sc. BIONORTE/UFMA

Portela, Larissa Brandão. Environmental benefits of the system of cultivation in alleys in the efficiency of the use of nutrients, with a view to the production of silage in the pre-amazon of Maranhão. 2018. 150 f. Thesis (doctorate BIONORTE) - Universidade Federal do Amazonas. Maranhão, São Luis, 2018.

ABSTRACT

In Brazil, alley cultivation is becoming an acceptable agroforestry practice in some regions. To better understand its potential to provide environmental benefits coupled with increased productivity, research involving alley cropping system has expanded significantly in the last decades. With the objective of improving the productivity and sustainability indices of small farmers in the Maranhão Amazon region, an alley cropping system was used to produce corn for silage production. A randomized block experiment with plots of 10 x 4 m^2 and four replications was used to evaluate growth and yield in the years of 2015, 2016 and 2017 and under an alley cropping system. of hybrid maize (AG1050) and QPM (BR743), using three species of tree legumes, *Leucaena leucocephala*, *Gliricidia sepium* and *Acacia mangium*. The efficiency of nitrogen use, nitrogen recovery efficiency, maize productivity, corn silage yield, carbon stock potential, decomposition and release of nutrients present in legume biomass and litter of the system, the weeding of weeds and the economic benefits, with the purpose of improving corn cultivation for silage in the Maranhão Amazon under an alley cropping system.

Key words: animal feed, agroforestry system, tree legumes.

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SUMÁRIO

Introduction

Some cities in the state of Maranhão are located in a transition region known as the Amazonian border, presenting great natural, social, economic, technological and cultural diversity (IBGE, 2014). This region presents a growing process of agricultural expansion, where the increase of deforested areas, high temperatures, agriculture based on cutting and burning practices, and the opening of native forests to pasture, constitutes a mixture of different uses of the region that has been changing the occupation of the Amazonian border in a radical and unsustainable way.

Some researchers this region, allied to small farmers, use agroforestry systems to improve soil quality and consequently increase their production. Agroforestry encompasses a diverse array of multifunctional practices that intentionally integrate trees or shrubs with crops or livestock into a single agricultural system (Gold and Hanover, 1987; Wilson and Lovell, 2016). Beyond their potential to improve agricultural productivity and resilience, agroforestry practices can promote carbon sequestration, biodiversity, nutrient use efficiency, pest resilience, and reduced soil erosion (Jose, 2009; Lorenz and Lal, 2014; Quinkenstein et al., 2009; Torralba et al., 2016; Tsonkova et al., 2012).

With respect to the biodiversity within the alley cropping system (AC), products from both tree and crop components can include food, fodder, fuel, biomass, medicine, and floral products, while the trees can also produce timber, sap, and cork (McAdam et al., 2009; Nair, 1991). These systems also have the potential to capture and store greater amounts of C in the biomass and soil compared with monocultures (Dieter and Elsasser 2002; Schoeneberger 2009; Bailey et al. 2009; Bambrick et al. 2010; Djomo et al. 2011). Additionally, they decrease deforestation in tropical regions (Montagnini and Nair 2004; Matos et al. 2011) and increase biodiversity (Sharrow and Ismail 2004; Peichl et al. 2006; Gibbons et al. 2008).

The cultivation of biofortified food in low-input, sustainable agroecosystems can be seen as a viable strategy to improve the nutritional status of families, raise the income of populations and mitigate a series of environmental problems (Souza, 2013). The cultivation of QPM (Quality Protein Maize) maize varieties by households farms can help greatly in the fight against protein deficiency because this cereal represents the major part of all protein consumed in the world's poorest regions (FAO, 2012). in addition, this corn when destined to animal feed in the form of silage raises its nutritional contents, favoring a greater weight gain. The QPM varieties have the same energy values when compared to traditional cultivars, but have higher lysine and tryptophan levels, two essential amino acids normally absent in the diet of families living below the poverty line (ZHAI et al., 2007).

Despite the wide variety of AC in Brazil, no research has been conducted to relate environmental benefits and silage production. An understanding of the benefits and possibilities of producing animal feed silage will guide the growing interest in CA and help identify research priorities.

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OBJECTIVES

To evaluate the environmental benefits of an agroforestry system, regarding corn nutrient use efficiency, as an alternative for the sustainable production of corn silage.

The specific objectives were:

1. Our primary goals were to catalog species composition and agricultural function in all publications of AC field experiments around the Brazil and use the resulting inventory to identify existing gaps and promising frontiers of AC research.
2. Investigate the application of tree leguminous residues to maximize maize production, nitrogen use and recovery efficiency, sustainability indicator and economic benefits.
3. Quantify organic C stocks in the above-and belowground tree biomass and in the soil in alley cropping system with different tree species.
4. Evaluate influence of soil cover and N and K fertilization on the quality of QPM maize silage in AC
5. Characterize the taxonomic and functional compositions of groups of weed communities in each maize variety, and to analyze the associations between weed communities and the management used in AC
6. Compare the release of nutrients between litterbags method with a method of direct collection of litter in AC

The following articles have been published based on the standards of the following journals:(1) Agriculture, Ecosystems and Environment, (2) Nutrient Cycling in Agroecosystem, (3) Agroforest Systems, (4) Archivos de Zootecnia, (5) Weed Science and (6) Journal of Agricultural Science, with adaptations to the thesis norms of the PhD course of the Graduate Program in Biodiversity and Biotechnology of the BIONORTE, Universidade Federal do Maranhão. The standards of the journals are in Annex 1.

Tree species composition and function used in Alley cropping in Brazil

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ABSTRACT

In Brazil the alley cropping is becoming an acceptable agroforestry practice in some regions. To better understand its potential to provide environmental benefits coupled with good productivity, alley cultivation research has expanded significantly in the last decades. Although the alley crop presented diversity of species in its composition and function, no comprehensive inventory of its various forms was performed. We analyzed the historical trends in species composition and function of all alley cropping experiments in the literature. A total of 281 publications over the last 12 years were included. Tree diversity was low across all regions, with 42 species utilized. Dominant

trees included with *Leucaena leucocephala* and *Clitoria fairchildiana*. Alley crops were more diverse (176 species) but were dominated by a few annual grains in each region. Despite the diversity in composition between systems, the agricultural functions of trees and crops were limited, and their use as facilitators and food was more common. In order to better guide the growing interest in alley cultivation in Brazil, this inventory was used to identify gaps in the literature and inform future opportunities in alley cropping research. three topics in alley crop research were identified as (1) Increase in the diversity of trees, (2) use of trees: food and fodder, (3) trees for crop facilitation.

Introduction

The alley cropping system (AC) is characterized by the handling of crops of interest that are cultivated in the corridors formed by the interlines composed by fast growing plants fertilizers. Fertilizer species are usually legumes that fix N, and have the potential to increase N levels in the soil after the deposition of their biomass (Yamoah et al., 1986; Lal, 1989). In the management of the system, legumes are pruned periodically to provide green manure or cover for the culture of interest established between the lines and to minimize root shading and competition between the associated crops (Atta-krah et al., 1986; Kang et al., 1990).

The geographic situation of the different regions of Brazil does not allow to use the same technology generated in alley cropping system (AC) or the technology of other countries, to solve the problems of productivity due to their specifics of soil and climate. For example, in some northern and northeastern regions the success of AC is related to the quantity and quality of the pruned material from trees, the amount of nutrients released from residues during the decomposition process, and the synchronicity between nutrient release and crop requirements (Mendonça and Stott 2003)

Despite CA are growing in Brazil, no comprehensive inventory of species composition and function in AC has yet been performed. An understanding of AC composition and function will orient the growing interest in AC and help identify research priorities. Therefore, our primary goals were to (1) catalog species composition and agricultural function in all publications of AC field experiments in Brazil and (2) use the resulting inventory to identify existing gaps and promising frontiers of AC research.

2. Methods

This study considers AC, defining the "tree" component as one or more trees or shrubs, and the "crop" component can refer to annual and perennial, herbaceous and woody plants that produce agricultural products. While “alley cropping” has been the term adopted by the agroforestry community in the Brazil and many other countries, other terms that refer to comparable systems are also widely used in the literature, including “agri-silviculture”, “tree-based intercropping”, “hedgerow intercropping”, “belt and alley systems”, “agrihortisilviculture”, “intercropped orchards”, “parkland systems”, “agri-horti systems”, and “multi-strata agroforestry systems” (e.g. coffee/cacao agroforestry and tropical homegardens) (Liu and Zhang, 2011; Mosquera-Losada et al., 2009; Nair, 1991; Williams and Gordon, 1992). These systems are all considered here aspects of AC.

This review considers publications on AC field experiments published in peer-reviewed journals. While an inventory of field experiments is not necessarily a direct reflection of AC being applied on farms, it nevertheless represents the depth and breadth of our scientific understanding of AC and is the best available approach to assess species composition and function in AC. Publications that did not include AC field experiments were not included in the review.

To find all publications on AC, a literature search was conducted on the Portal de Periódicos CAPES/MEC requiring one or more of the following key phrases: “agroforestry”, “alley crop”, “silvoarable”, and “intercrop” or “tree” with “Brazil”. The search query was constructed so studies that only examined other agroforestry systems (i.e. silvopasture, riparian buffers, windbreaks, and forest farming) but not AC were not returned (Table S2).

The search found 2.116 publications using a search window of 2006 through 2018, and included all major journals with AC-related publications (Fig. S1). All selected publications were examined to determine if the criteria were met for inclusion in the inventory, with a total of 281 publications meeting the criteria. All analyses were conducted at the species level. Analyses of tree and crop composition and function were performed using the unique combinations of publication-tree species or publication-crop species as the experimental units (referred to here as “observations”). The full catalog of reviewed publications and observations is available in the Supplemental Materials.

Results and discussion

Year and focus of research

The retrieved publications on AC field experiments spanned 23 years, with the earliest in 1990 (Fig. 1). This horizon corresponds well with the broader historical origins of agroforestry in Brazil. The term “agroforestry” was coined in the mid-1970s, the International Council for Research in Agroforestry (ICRAF, now the World Agroforestry Centre) formed in 1978 (Huxley, 1987), ICRAF’s work remains primarily focused on the tropics. The publication record similarly began in the tropics and the number of tropical publications continues to grow at a faster rate than in other regions. However, beginning in the early 2000s, the tropical research focus shifted sharply to the more complex coffee/cacao and maize systems (Fig. 1). This shift was likely driven by increasing consumer demand for extensively managed and shade-grown coffee/cacao and the resulting research funds contributed by the industry.

As the scientific literature on agroforestry grew, the journal Agroforestry Systems began publishing in 1983. By 2009–2018, the number of publications on AC field experiments in Brazil grew to just under 25 publications per year. Overall years, 12% of publications were published in Agroforestry Systems. The next most common journals were Pesquisa Agropecuária Brasileira, Revista Árvore, Ciência e Agrotecnologia and Nutrient Cycling in Agroecosystems at 10.7%, 5.3%, 4.6% and 4.3%, respectively (Fig. S1).

3.2. Tree component: species composition & function

Across all publications, 42 species were represented in the tree component of AC field experiments (Fig. 2). Tree richness across systems increased towards the southeast, with 5.2 times as many species found compared to north and northeast of the country. Studies were dominated by just a few species, with *Leucaena Leucocephala* and *Clitoria fairchildiana* in 23% of publications, are both nitrogen fixers and have been used extensively as a “chop-and-drop” fertilizer for annual grain crops in AC, followed by *Gliricidia sepium* and *Eucalyptus urophylla* with 16% of publications.

There were 33 publications containing *Leucaena Leucocephala*, respectively, more than double that of any other tree species in any region. Eucalyptus was the most common tree species, although the southeast contained a more even distribution of utilized tree species. Beyond composition, the functional role of the tree component in AC was different in the publications (Fig. 3). The primary function of the tree component in 48% of observations was trees for crop facilitation via shade, nitrogen fixation, and mulch production. The only other significant tree function was biomass (wood) and food production. Food production included both *Coffea arabica*, *Zea mays*, *Theobroma cacao* and *Manihot esculenta*, while fodder production was primarily green leaves and branches in "cut-and-carry" systems.

The trees responsible for facilitating in systems in aleias increase productivity relative to monoculture yields (Cannell et al., 1996; Vandermeer, 1989). In the reviewed literature, there were three primary ways in which trees were used to facilitate crop productivity: nitrogen fixation, shade, and mulch production.

The abundant use of nitrogen-fixing trees in Brazil demonstrates the emphasis in these regions on multi-purpose trees. Many trees that were classified as having non-facilitative primary uses were also nitrogen fixers and, consequently, likely contributed to crop facilitation as well (Fig. 3).

Beyond nitrogen fixation, AC commonly leveraged trees to provide mulch production. The use of residue cover may impart physical and chemical soil improvement effects to deeper layers, thereby improving the soil structure in terms of root growth. In many areas of the humid tropics, high temperatures and copious rainfall, combined with soils derived from clastic sedimentary rocks, result in low nutrient availabilities and unfavorable conditions for continuous crop cultivation (Moura et al., 2012). In these systems, multiple facilitation mechanisms were often provided by the same tree species.

Crop component: species composition & function

The crop component of AC field experiments was also very diverse across all publications, with 176 species represented (Fig. 4). The studies were dominated by four crops: *Zea mays*, *Coffea arabica*, *Theobroma cacao* and *Manihot esculenta*. The 72 total publications containing Zea as the alley crop pairs directly with the dominance of Leucaena and Gliricidia in the tree component discussed above. The Leucaena-Zea and

Gliricidia-Zea systems constitute the most-studied AC systems to date. Despite the diversity of crops utilized, food production was the dominant crop function (Fig. 5).

Other common crops included: Ananas, Cucurbita moschata, Avena strigosa, Carica papaya, Gossypium hirsutum, Crotalaria juncea, Glycine max, Oryza sativa and Phaseolus sp.

Future research priorities

An understanding that encompasses all aspects of experimentation in the AC is very important to guide future research. The remainder of this paper discusses three gaps in species composition and function in AC research that were identified in this analysis as opportunities for future research and application.

Topic 1: Increase the diversity of trees

Diversity is inherent in AC, with the definition requiring at least two species – one tree or shrub and one crop. However, despite the diversity of trees utilized across AC systems (Fig. 2), diversity within the tree component of individual AC systems has been very limited. In the north and northeast of the country the trees are used as facilitators, where the residues are deposited to the ground as mulch. these wastes are defined as "high or low quality". The definition of high and low quality wastes according to Young (1997), which defines high quality residues as those with high N content, low amount of lignin and polyphenols; and the reverse must be termed low quality waste. even using these combinations, the diversity of trees in Brazil's AC is still limited.

It was observed several studies where the diversity of trees was not declared and the wealth unknown or not reported (Fig. 6). These cases occurred almost exclusively in coffee and cocoa systems with high diversity of shade tree species or in backyards with high diversity of species. this indicates that the fact that numbers and species are not reported in these studies illustrates that the use of diversity was probably not intentional within AC. Often, the diversity of these systems was only a consequence of the remnant population of native trees under which the system was established. Key research opportunities are related to finding new species for intentional integration and management of tree diversity within the CA.

Topic 2: use of trees: food and fodder

As well as exploring new tree species is relevant to CA, food production and fodder can also be improved. However, in observing this analysis we verified that this function is limited to the culture component (Figs 3 and 5). Only 25% of CA observations included trees for feed or forage, compared to 75% for crops, wood and sap. Smith (1929) reviewed the potential of a wide range of tree crops for food and fodder production; he described the “meat-and-butter” trees of Juglans and Carya, the “corn trees” of Castanea (chestnut) and Quercus, the “stock-food trees” of Ceratonia (carob), Prosopis (mesquite), Gleditsia (honey locust), and Morus (mulberry), and a “kingly fruit for man” in Diospyros (persimmon). Smith’s work has inspired agroforestry for almost 90 years, and his vision for staple tree crops is no less relevant today (Molnar et al., 2013). Yet, the results of this analysis clearly demonstrate that little of Smith’s vision of tree crops for food and fodder has translated into tangible research and field experimentation in AC.

In the tropics of Brazil, the production of food from agroforestry systems is the main adoption factor, especially in low income and subsistence farming communities. In these systems, the use of trees serves to produce straw to cover the soil and make it arable. The crops grown in this system are for subsistence. in another aspect, to choose species that have dual aptitude (human feeding and soil cover) as an effective alternative for small farmers.

Topic 3: trees for crop facilitation

The experiments have more frequently used trees to facilitate and increase plant productivity through nitrogen fixation, shade and mulch production (Fig. 3). Nitrogen is the largest and most expensive input to row crops. Massive applications of highly mobile inorganic nitrogen lead to considerable negative impacts on water quality via nitrate leaching (David et al., 2010). N losses have considerable negative impacts on water quality via N leaching and climate change via soil emissions of nitrous oxide (N_2O), a potent greenhouse gas. AC focused on food- or fodder-producing tree crops has the potential to substantially reduce environmental N losses while maintaining agricultural productivity.

Opportunities exist for expanding the use of nitrogen-fixing trees in AC in the tropics. *Pereskia aculeata* and *Moringa oleífera* there are examples of species found in this review that present a large amount of nitrogen and its composition that could be more exploited.

On-farm mulch production is another facilitation mechanism that could benefit from the use of more N-rich species. Rapidly expanding around the world, organic crop production systems often utilize mulch as an important weed control strategy (Wilson and Lovell, 2016), however, in the humid tropics, its use goes far beyond that.

Alley cropping in association with no-tillage can be an efficient strategy to maintain productivity in the low-fertility soils of the humid tropics because of its capacity to recycle nutrients and improve soil quality indicators over time, in addition increased soil aeration capacity, moderation in the amounts of additional N, and buffering of Ca levels in the root zone (Aguiar et al., 2010).

In the humid tropics, crop residues alone are insufficient to cover the soil, due to the fast-post-harvest decomposition (Aguiar et al., 2010). It is also important to emphasize that the use of certain tree species used as mulch also presents rapid decomposition, resulting in lack of synchronization with the release of nutrients and the requirement of the crop. In this region combinations of tree species are used in the AC with the objective of combining longer soil cover and slow release of nutrients.

4. Conclusions

The use of alley cropping system can transform the agricultural landscapes, improving the ecological function and maximizing the production. Here, we cataloged the species composition and function in all AC field experiments published over the last 12 years. This inventory of the diversity of AC research provides robust context and direction for orienting future research in Brazil. Overall, AC field experiments to date have utilized 42 tree species and 176 crop species. Both trees and crops provided a wide range of agricultural functions, although tree and crop functions were focused on facilitation and food production, respectively. Within-system diversity has been primarily limited to just a single tree and single crop species. Major topics for AC research were identified as (1) Increase the diversity of trees, (2) use of trees: food and fodder, (3) trees for crop facilitation. These topics should be the focus of future research, expanding our understanding of AC systems and bringing improvements to local producers.

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Supplemental Materials

Table S1. Specific types of publications and systems that were not included in the review.

1. Publications on purely *in silico* modeling, stakeholder surveys, or economic analyses,
2. Experiments based in the laboratory or greenhouse
3. Reviews/syntheses of other studies
4. Studies at the landscape level in which AC was only one component
5. Mixed-species forestry and orchard systems in which no crop component could be identified
6. Silvopasture systems or any agroforestry systems that integrated livestock, although AC in which a fodder crop was grown as hay were considered
7. Shelterbelts, windbreaks, hedges, forest farming, or riparian buffers
8. “Improved fallows” as part of crop-fallow rotation agroforestry, since these do not include trees and crops coexisting in space
9. Field studies on species regarding their potential in AC but that were not performed in AC

Table S2. The Web of Portal Periódicos CAPES/MEC query used to retrieve the 281 publications screened for inclusion in this review.

(TS=(agroforestry OR "alley crop*" OR "silvoarable" OR ((orchard OR tree) AND intercrop*))

NOT TS=(silvopast* OR silvipast* OR "riparian * buffer*” OR windbreak* OR "forest farming”))

OR (TS=("alley crop*" OR "silvoarable" OR ((orchard OR tree) AND intercrop*))

AND TS=(silvopast* OR silvipast* OR "riparian * buffer*” OR windbreak* OR "forest farming”))

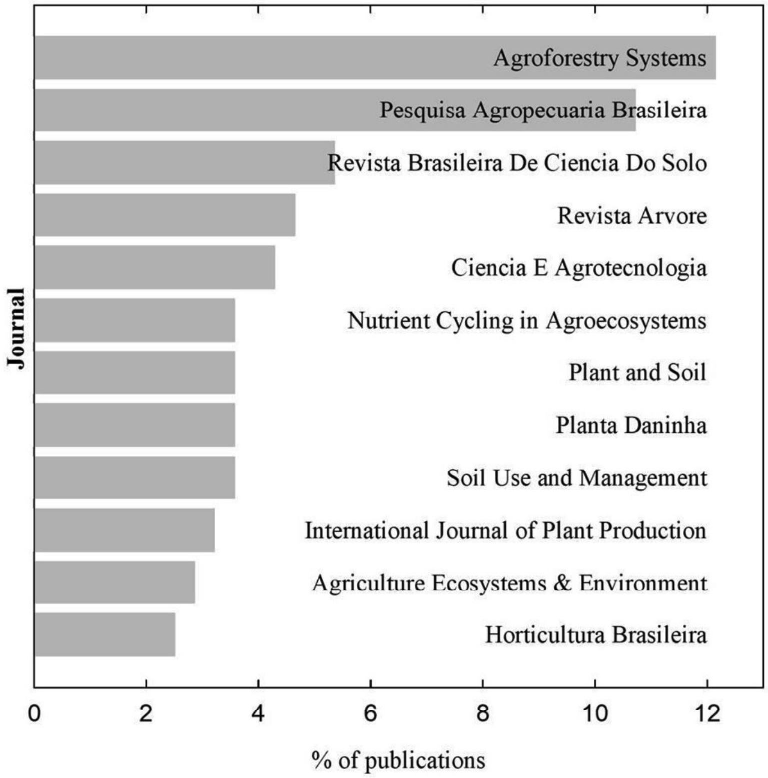

Fig. S1 Proportion of reviewed publications published in the 10 most encountered journals.

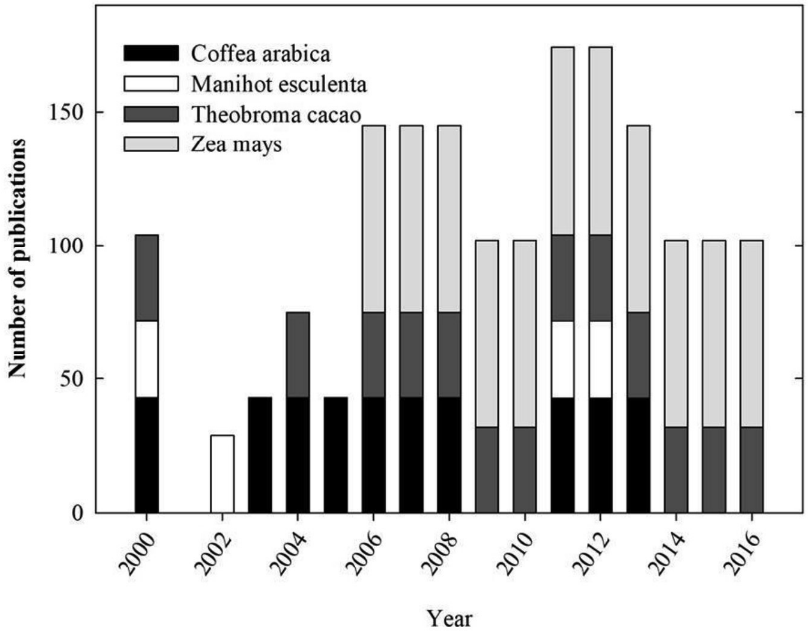

Fig. 1. Historical trend of peer-reviewed publications on AC field experiments

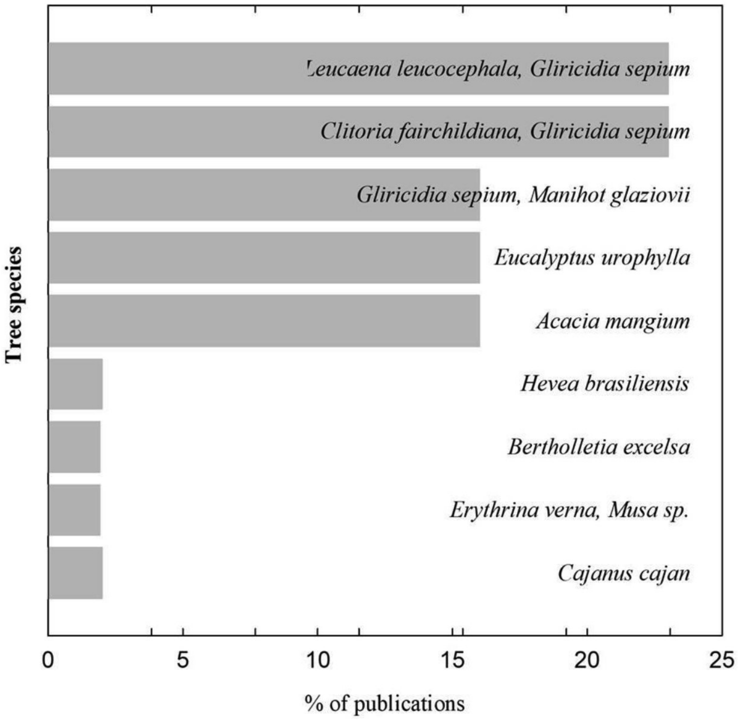

Fig. 2. Frequency of species occurrence in the tree component of AC field experiments.

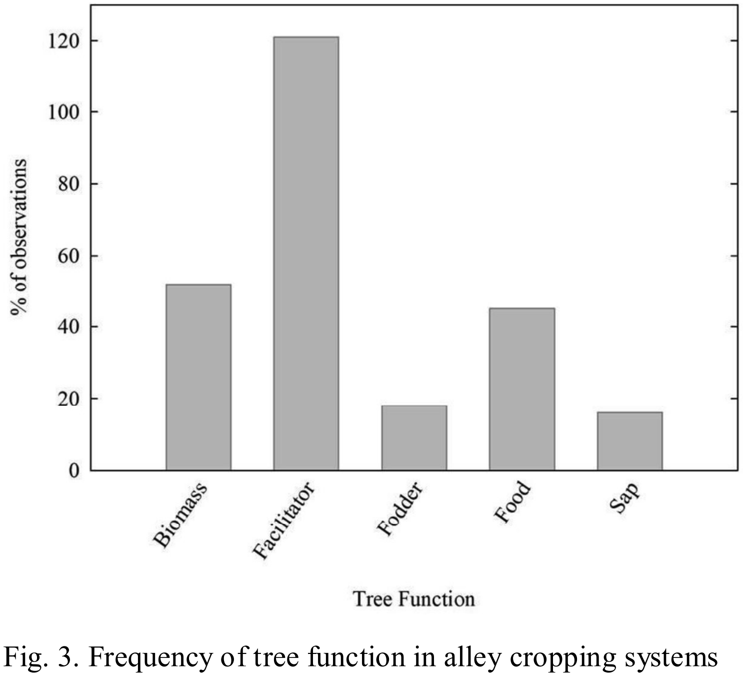

Fig. 3. Frequency of tree function in alley cropping systems

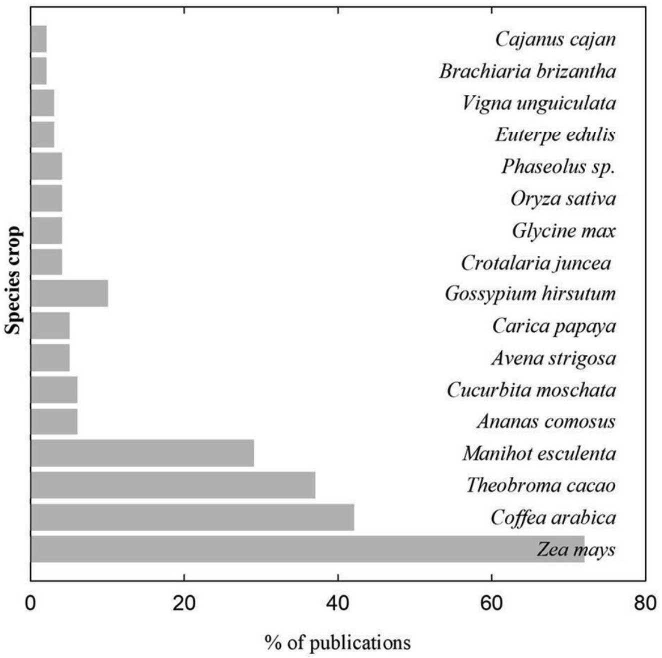

Fig. 4. Frequency of species occurrence in the alley cropping system. Since many experiments examined multiple alley cropping systems, often with different crop species, the sum of values is not 100.

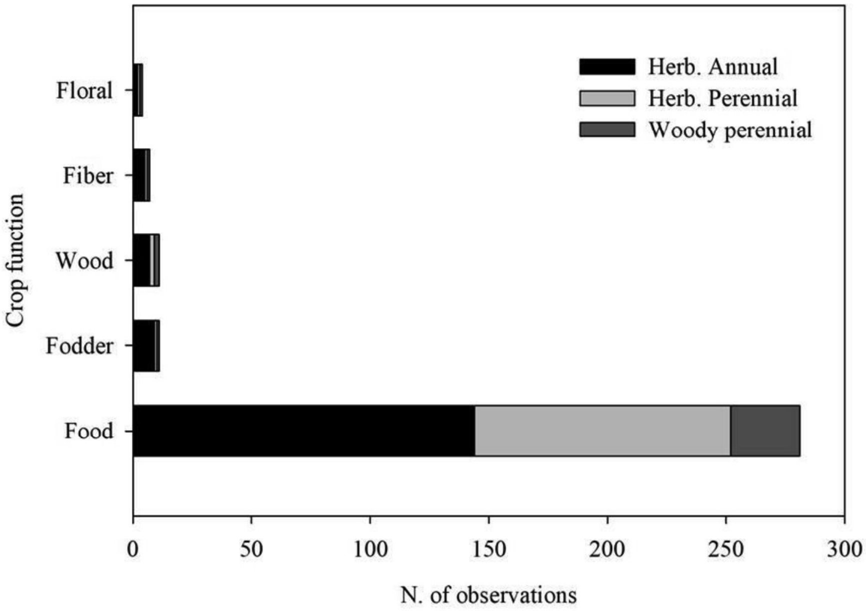

Fig. 5. Frequency of crop function in alley cropping system.

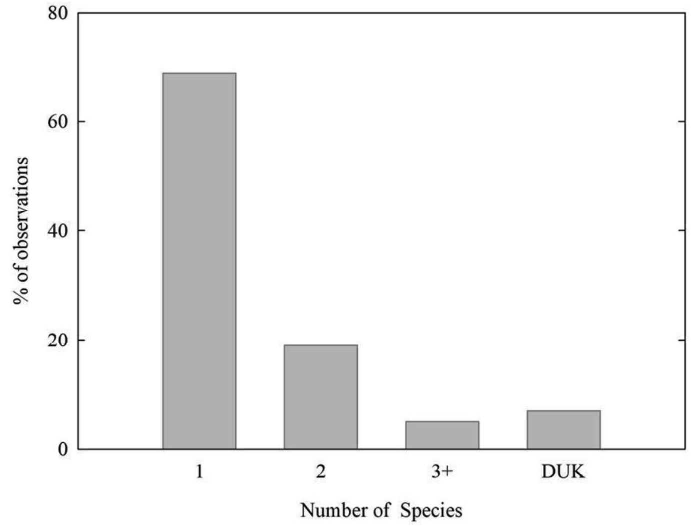

Fig. 6. Number of species included in the tree and alley crop components within individual AC field experiments. DUK (diverse but unknown) refers to diverse treatments containing an unknown number of species.

Maximizing maize quality, productivity and profitability through a combined use of residues and nitrogen fertilizer in periphery of Amazonia

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Abstract: In periphery of Amazonia, low crop yields are a common problem of in sandy loam soils. Poor nitrogen use efficiency (NUE) and widespread soil nitrogen (N) deficiency resulting from higher N losses are the main reasons for low yields. Residues may offer a nutrient source in this context as it is relatively stable, has a high NUE and crop N uptake, and may contribute to lower N losses in this region. This research conducted during 2015, 2016 and 2017, The treatments consisted of tree types of residue: *Gliricidia sepium* (G) *Acacia mangium* (A), *Leucaena leucocephala* (L), urea (N), G+N, A+N, L+N, and control (C), for sustainable maize production under the peripheral region of the amazon. Overall, combined use of G or A with urea in the 3 years increased the grain yield relative to the application of G or A alone and urea on their own. The greatest plant N uptake during the three years of G+N and A+N was higher to than mineral N, and it resulted in maximum total grain yield (4.8 Mg ha^{-1}) and grain protein (3.2%). This resulted in the lowest N loss from the soil, and the largest NUE (14.3 kg kg^{-1}) for the A+N treatment. Economically, A+N treatment also provided the greatest net income (1169.7 US$ ha^{-1}) Based on these results, A+N was considered highly beneficial in increasing maize yield while reducing the loss of less-stable N from the soil, increasing NUE and N uptake in inherently poor soils.

Keywords: Leguminous trees, Nitrogen use efficiency, alley cropping system.

Introduction

In the periphery of Brazilian Amazonia, agricultural researchers find it extremely difficult to establish low input agricultural systems that are suitable for smallholders without resorting to the environmentally harmful practice of slash and burn. Challenges arise from a combination of factors that reduce crop nutrient use efficiency (Aguiar et al., 2010).

Nitrogen (N) is one of the crucial elements for crop production to achieve high crop yields (Erisman et al., 2008). However, a widespread N deficiency in agricultural fields (Ladoni et al., 2015) and poor nitrogen use efficiency (NUE) as a result of higher N losses from applied fertilizers hamper crop yields. N deficiency and low NUE problems are prevalent, especially in coarse textured soils (eg sandy clay) with low water and nutrient retention capacity and substantial nutrient leaching (Waddell and Weil, 2006). One of the causes of these losses of N in these soils is the rigid adjustment, caused by repeated cycles of wetting and drying in soils with low levels of free iron and organic carbon. This reduces soil volume as described by Mullins (1999) and impairs N uptake. In addition, the humidity caused by dew in this region exerts influence on the urease activity, causing losses by volatilization, high temperatures increase ammonia volatilization and accelerate bacterial ammonium nitrification (Mikkelsen 2009), as well as degradation of Reserves of organic soil N (Guntiñas et al., 2012)

Exact measurements are not available for reductions in N and NUE availability after such N losses of sandy and clayey soils from arid and semi-arid agroecosystems, but are likely to be substantial. To reduce losses and to maximize sustainable food production, it is necessary to adjust the nitrogen fertilizer. One of the strategies to reduce N losses, increase N availability and NUE is the incorporation of organic residues into soil so as to increase soil organic matter, aeration, water and nutrient holding capacity and total plant activity besides the additional N and other nutrients (Zhou et al., 2014, 2016).

However, different organic residues may have positive or negative effects on the production system, depending on their composition. No-till alley cropping systems of leguminous trees must provide adequate levels of residue to provide good soil cover for the soil-crop system between the rows while maintaining or increasing root-zone nutrients for these crops. This tends to be easier in the humid tropics where trees grow quickly, increasing the yield of biomass and nutrient recycling (Moura et al., 2008).

Thus, the main objective of this study was to investigate the application of N from leguminous trees residues in combination with urea for sustainable maize production in sandy loam soils in the periphery of Amazonia. The research hypothesis was that application of residue alone substantially increases the maize yield, and mixing/integration of residue with urea as N sources is an effective fertilization strategy to generate the greatest benefits and income.

Materials and methods

Site description

The experiment was performed in an experimental field in Chapadinha, Maranhão, Brazil at 3° 44′ 30″ S and 43° 21′ 37″ W, which is located in the northeast of the country. The region has a hot and semi-humid equatorial climate with a mean precipitation of 2100 mm year^{-1} and two well-defined seasons, a rainy season that extends from January to June and a dry season with a water deficit from July to December (Fig 1). The soil in the experimental area is an Arenic Hapludult.

Design and treatments of field experiments

The experiments were conducted in a randomized complete block design with four replicates in a plot size of 10 m x 4 m, totaling 1.280 m^2. The treatments consisted of tree types of residue: *Gliricidia sepium* (G) *Acacia mangium* (A), *Leucaena leucocephala* (L), *Gliricidia sepium* + urea (G+N) *Acacia mangium* + urea (A+N), *Leucaena leucocephala* + urea (L+N), Bare soil + urea (BS+N) and control (C). Urea (46% N) were used in order to meet the recommended N (120 kg ha^{-1}) for maize in each treatment.

Residues production and analysis

The leguminous were sown in 4 m spaces between rows and in 0.5 m spaces between plants, which resulted in 10 m × 4 m plots. The experiment was conducted under a no-tillage system and the leguminous were sown in 2013. The leguminous trees were pruned every year. The tree pruning biomass was distributed homogeneously throughout all plots. After then corn was sown at a spacing of 0.5 m between plants. The amount of applied biomass and chemical properties are described in Table 1.

Fertilizer management and crop cultivation

The appropriate residue was applied after calculating the correct amount to reach the level of N needed for each treatment (120 kg N ha^{-1}), and applied at the time of sowing of maize seed. The plots that received mineral fertilization were fertilized with 60/40/80 kg ha^{-1} of N/K_2O/P_2O_5 in the forms of urea/potassium chloride/Triple superphosphate divided into two applications: one at the time of sowing and another at the appearance of the fourth pair of maize leaves. The crop area had been in fallow since June 2014 and the maize was planted in 2015, 2016 and 2017, between the rows of leguminous trees, variety AG 1053 at a spacing of 0.5 m between plants and 1.25 m between leguminous trees .

Data recording

Agronomic aspects

Data on yield were recorded by harvesting two central maize rows from each plot. The plants and cobs were air-dried, and in a forced air circulation oven, weighed and their yield in (Mg ha^{-1}) calculated. The cobs were threshed, the grain weighed and converted into yield in Mg ha^{-1}.

Sustainable yield index (SYI) was determined following the procedure of Singh et al., (1996):

$SYI = (y - \sigma_{n-1})/y_m$ (1)

Where y is the mean grain yield (Mg ha^{-1}), σ_{n-1} is the standard deviation, and y_m is the maximum grain yield (Mg ha^{-1}) among all the treatments.

Harvest index was calculated by using the formula (Hunt 1978):

$$HI\ (\%) = \frac{Y_G}{Y_B}\ x\ 100\ (2)$$

Where HI is the harvest index (%), Y_G is the grain yield (Mg ha^{-1}), and Y_B is the total plant yield (Mg ha^{-1}).

For grain protein, first the total N in grain samples was determined by using method of sulfuric acid digestion and distillation by the micro-Kjeldhal method (Helrich 1990). The N percentage was then multiplied by a constant factor of 6.25 to calculate the protein content in the grain. The Soxhlet fat extraction method was followed to determine the oil content in grain samples as described by Low (1990).

Nitrogen use efficiency (NUE) was calculated with the following formula (Zhang et al., 2016):

$$NUE\ (Kg\ Kg^{-1}) = Y_F - Y_{CTRL}/N_F\ \ (3)$$

Where Y_F is the grain yield (kg ha^{-1}) in the fertilized treatment, Y_{CTRL} is the grain yield (kg ha^{-1}) in the control treatment, and N_F is the total amount of N (kg ha^{-1}) applied in the fertilized treatment.

For nitrogen recovery efficiency (NRE), random plant samples including stalks, leaves and grains of maize plants from each plot were ground, and the N concentration was determined by the Kjeldhal digestion method of Bremner and Mulvaney (1982). Then N uptake was determined with the formula (Keeney 1982):

$$N_{UPT}(Kg) = N_{cnc}\ \mathrm{x}\ Y\ \ \ \ (4)$$

Where N_{UPT} is the N uptake (kg), N_{cnc} is the N concentration (%) in the treatment sample, and Y is the maize yield (kg ha^{-1}).

After that nitrogen recovery efficiency (NRE) was calculated from the following formula (Zhang et al., 2016):

$$NRE(Kg\ Kg^{-1}) = U_T - U_{CTRL}/N_F\ \ \ \ (5)$$

Where U_T is the N uptake (kg) in the fertilized treatment, U_{CTRL} is the N uptake (kg) in the control, and N_F is the same as in Eq. 3.

N vulnerable to losses through volatilization, leaching and denitrification was determined with (Zhang et al., 2016):

$$N_{VUL} = N_F - N_{UPT} \quad (6)$$

Where N_{VUL} is the N vulnerable (kg ha^{-1}) to different losses, N_F (kg ha^{-1}) is the same as in Eq. 3, and N_{UPT} is the same as in Eq. 4.

Economic aspects

The experimental data of both years were analyzed for gross and net income and benefit cost ratio by using the methodology described in CIMMYT (1988). All the items including the cost of manpower, transportation, fertilizers, seed, tillage, cultivation and harvesting, as well the local markup of 9% per annum on investment were included to calculate the total cost. The gross income was calculated as:

$$GI = Y \text{ x } P_M \quad (7)$$

Where GI is the gross income (US\$ ha^{-1}), Y is the yield (Mg ha^{-1}), and P_M is the local market price (US\$ ha^{-1}). The net income (US\$ ha^{-1}) was calculated as:

$$NI = GI - TC \quad (8)$$

Where NI is the net income (US\$ ha^{-1}), GI is the same as in Eq. 7, and TC is the total cost (US\$ ha^{-1}).

The benefit cost ratio (BCR) was then computed for each treatment as follows:

$$BCR = \frac{GI}{TC} \quad (9)$$

Where GI is the same as in Eq. 7, and TC is the same as in Eq. 8.

Statistical analysis

All statistical analyses were completed using INFOSTAT software (2010). All variables were tested of normality distribution. We conducted an analysis of variance followed by the Tukey-test at $p<0.05$.

The graphical software and statistical package in SigmaPlot10.0 was used to implement a simple linear regression model to ascertain the relationship between maize N uptake and agronomic aspects. SigmaPlot10.0 was further used to ascertain the relationship between maize N uptake and various agronomic aspects by implementing the following simple linear regression model (Thierfelder et al., 2016):

$$Y_{ij} = \mu_i + \beta_{i\mu j} + d_{ij} \quad (10)$$

Where Y_{ij} is the *i*th treatment mean by the *j*th N uptake, μ_i is an effect of the *i*th N uptake, β_i is the regression coefficient to the *i*th treatment, μ_j is an effect of the *j*th N uptake, and d_{ij} is the distance from the regression line (Eberhart and Russell 1966).

Results

Weather scenarios

During three experimental seasons, the rainfall received during 2015 was higher than 2016 and 2017, and the temperature recorded during three years were similar (Figure 1).

Agronomic aspects

Total plant yield was significantly increased ($P>0.05$) in all the treatments during three maize growing years (Table 2). Total plant yield was significantly higher ($P>0.05$) in year 3 (2017) than in year 1 or 2 (2015 and 2016). During the three years, the combination of *Acacia mangium* and *Gliricidia sepium* with urea (A + U and G + U) increased the total yield of the plant more than other leguminous or urea alone (Table 2).

However, C (without addition of nitrogen or leguminous) had the lowest yield. A significant correlation ($P < 0.05$) and a very close correlation between N uptake and total plant yield were observed (Fig. 2).

The combination of residues and chemical N increased significantly ($P<0.05$) grain yield (Table 3). In the three years, grain yield was higher for the combined use of G + N and A + N than the application of residues or urea alone. In year 3, for the G+N, grain yield was 16% higher than in year 1 or 2, and for the A+N, grain yield was 11% higher than in year 1 or 2. The smallest yield response was recorded in C. The linear regression model showed a significant ($P<0.05$) and strong correlation between N uptake and grain yield (Fig. 3).

Harvest index was significantly increased ($P<0.05$) by treatments L+N, A+N, G+N and BS+N (Table 2). There was no significant difference ($P<0.05$) in years 1, 2 and 3 for the harvest index for the treatments G+N and L+N, and A. The harvest index varied between 9-47% in year 1, 27-49% in year 2 and 29-48 % in year 3. In year 1 a significantly higher harvest index was recorded in the treatments L + N in all years. The lowest value of the harvest index was in treatment control.

The sustainable yield index (SYI) ranged from 0.05 to 1.0; 0.06 to 0.83 and 0.06 to 0.85 in year 1, 2,3 respectively. (Fig. 4). In general, the SYI was improved where the residue was combined with urea compared to the residue alone over the two years. The highest SYI was in G + N treatment while the lowest was in treatment C.

Grain protein was not statistically different ($P<0.05$) across years, but was statistically different ($P<0.05$) among treatments for three years (Table 3). Residue and urea treatments showed significant increases ($P<0.05$) in grain protein content in the three years. Conversely, grain protein content was lowest in C treatment.

During three years, a significantly ($P<0.05$) strong correlation existed between N uptake and grain protein content (Fig. 5). All the treatments significantly increased ($P<0.05$) the grain oil content during three years (Table 3).

During three years, the greatest grain oil content (4.3%) was recorded in the C treatment and the smallest oil content was recorded in the G+N in the three years. There was a significant ($P<0.05$) and strong negative correlation ($r = -0.94$) between N uptake and grain oil content (Fig. 6).

Maize N uptake versus N susceptible to losses to volatilization, leaching and denitrification was significantly increased ($P>0.05$) by the treatments G+N and A+N (Fig. 7), and was statistically higher ($P>0.05$) in year 3 compared to year 1 or 2 (Fig. 8). During three years, G+N and A+N resulted in higher maize N uptake and lower N loss (Fig. 7). The lowest N uptake was recorded in C.

Overall, the treatments with residue had higher value of NRE when compared to treatments without residue. In three years, NUE obtained greater benefits from the integration of residues and urea than from the exclusive use of residues. The highest NUE was reached by the A + N treatment in the three years (Table 4).

Economic aspects

Economic analysis revealed that in year 2, a greater gross and net income and BCR was attained than in year 1, except for the C. The combinate treatments returned higher gross income than residue-alone treatments (Table 5). However, only the treatment G + N and A + N presented net income superior to the other treatments. Treatments A and G presented the highest values of BCR.

Discussion

The unsustainable use of the soil of the deforested area on the Amazonian frontier is one of the greatest threats to the tropical forest, so the sustainable management of these soils with low natural fertility is a great challenge for the agriculture of small farmers in the humid tropics (Brady, 1996). In addition, in regions bordering the Amazon, such as the northeastern part of the state of Maranhão, which are agricultural frontier areas where the original vegetation has already been devastated, there is now a huge social bloc represented by a large contingent of farmers living below the line of poverty. It is no coincidence that many of Brazil's poorest cities are located in this region, with a human development index ranging from 0.498 to 0.467 (Fearsnside, 2002).

This research investigated the effect of tree leguminous residues on low fertility soils in the Amazon border region and was guided by two hypotheses: (a) maize yield is substantially increased by application of residues alone and (b) a combined application N fertilizer with residues accepts the greatest benefits and return on investment. The study accepted the first hypothesis that the residue alone significantly increased maize yield and other yield indicators, and accepted the second hypothesis that the application combined with N supplementation would be more beneficial than the residue alone. This research over the three years of the study indicated that the applications of residues in different proportions with urea in the humid tropics had a general positive effect on the total yield of the plant.

The combined use of residues and urea increased yield in year 1, and this increase was repeated in year 2 and 3, which suggests that a combined application of both inputs is more supportive of higher yields in frontier Amazon regions than application of these inputs on their own. This difference in yield between residue + urea and residue or urea alone was likely associated with N uptake. Similarly, in a previous study it has been observed that co-application of both fertilizers resulted in higher yields in sandy loam soils in the periphery of Amazonia (Moura et al., 2010).

The greatest yields in G+N and A+N suggests that it could replace traditional chemical fertilization in the study region. Farmers could also reap other benefits with this approach including enhancement of soil organic matter, water holding capacity, aeration etc. alongside a provision of essential plant nutrients (Kumar et al., 2011).

Nitrogen (N) is a major yield-limiting element in maize (Alemayehu and Shewarega 2015), and the soil of this study was deficient in N and organic carbon. Despite this poor status, the observed grain yield was higher (4.9 t ha^{-1}) than previously reported (3.5 t ha^{-1}) yields from Aguiar and Moura (2003) from studies conducted in this same region of the Amazon frontier, which confirmed the beneficial effects of using residues.

The application of residue alone (L, G or A) is not able to provide increases in yield when compared to the type of common fertilization used in the region. According to an earlier study (Garrido et al., 2017), they showed that the residue of *Gliricidia sepium* alone cannot be promoted in such environments because it does not meet crop needs, ultimately affecting yields of crops. It is worth noting that the reported maximum grain yield (2.2 t ha^{-1}) of G was much higher than the maximum yield (0.9 t ha^{-1}) reported by Garrido et al., (2017) using the same residue of *Gliricidia sepium* in the semiarid northeast of Brazil.

The tree biomass production of *Gliricidia sepium* was superior to the others, reaching 12.5 Mg ha^{-1}, but this superiority did not increase yields. This indicated that the quality and not quantity of the residue is of great importance in such evaluations. In addition, it is notable that the combination of G+N or A+N increased grain yield more than urea on its own. This implies that farmers cannot safely substitute nitrogen fertilizers for the residues alone, but they can add the residue combined with urea to obtain higher yields.

The sustainable yield index (SYI) determines how close a treatment is to sustainability (Reddy et al.,1999). A higher SYI from a combination of residue and urea rather than residue alone suggests that integrated use is more sustainable. The largest SYI, which was close to 0.7 during three years, was observed following application of G+N, and this implies that an ideal N fertilization strategy was reached that could also sustain yield (Reddy et al., 1999).

Harvest index depends mostly on the grain yield (Unkovich et al., 2010) e.g. a higher harvest index in a combined application of residue and urea over residue alone can be explained by the production of higher grain yield. This indicates that N applied in the form of residue also may not be adequately available, therefore, it is not directly translated into grain yield to achieve a greater harvest index. The highest harvest index resulted from combinations of either of G+N or A+N. This supports the existence of synergies between different N sources that then lead to increased utilization of a relatively large proportion of assimilates throughout the development process of plants (Lincoln and Edvardo 2006). In the present study, such enhanced utilization may have enabled the increase in the grain yield component of the harvest index.

Plants immediately convert increased supplies of N into protein (Rastgou et al., 2013) as protein formation is highly correlated with the availability of N (Shah et al., 2008). Higher protein status is also known to increase the low nutritional value of maize (Chaudhary et al., 2013). The N deficient sandy-loam soils of our study produce low quality food because high percentages of the applied N are being lost. In this study, residue applications over the three years produced grain protein percentages well below the average protein level (8%) required for optimum nutritional status (Hurburgh, 2003).

This shows that the application of residues in this region could produce better quality foods, but would not yet meet the minimum of desired protein. However, an integration of residue and urea in particular, G+N and A+N increased grain protein to a maximum in all years, which confirmed that this fertilization strategy has a greater potential to produce better quality food. Similarly, in a previous study the highest grain protein (9%) was recorded after application of *Gliricidia sepium* and 120 kg N ha^{-1} (Marques et al., 2017).

The lowest grain oil content was recorded in treatment G+N and this was also reflected in A+N where greater N uptake was converted into higher protein levels, while decreasing oil content. This was previously reported by James (2004), who showed a negative correlation between grain oil and N uptake (see also Fig. 6). Although the treatments without the addition of urea, and the treatment with urea only showed low yield, the oil content in the grain was high. Moreover, a tablespoon of maize oil satisfies the requirements for essential fatty acids for a healthy child or adult (CRA, 2006). However, the low reduction in grain oil may not have influenced the nutritional value of the grain. Another study (Iqbal et al., 2010) has confirmed that there is only a small reduction in grain oil when certain nitrogen treatments are applied.

Nitrogen (N) fertilization is associated with a range of environmental hazards (e.g., deterioration of above/ underground water quality, emission of N_2O gas, and biodiversity degradation) (Zhou et al., 2013), affecting crop productivity and profitability (Zhang et al., 2016). In general, high rates of N application exceeding the plants needs in this study resulted in an increased risk of N losses in all the treatments. Similar risk has been reported by many studies (Zhou et al., 2014) due to high rates of N application to agricultural lands. However, higher N uptake leading to better crop performance reduces the risk of N loss (Erisman et al., 2008).

During three years of the current study we observed higher plant N uptake when residue and urea where applied in combination relative to residue alone, which indicates that the combination is effective in improving the supply of N to plants and reduces the risk of its loss. Other studies (e.g., Aguiar et al., 2010; Leite et al., 2008; Vanlauwe et al., 2011) have also shown that an integration of residue and mineral fertilizer is effective for higher plant N uptake and as a mechanism to reduce N losses from sandy soils.

Lower N uptake in residue alone was due to asynchrony between the release of N and the needs of plant at different development stages as reported in earlier studies (Moura et al., 2010), and thus resulted in greater risk of N loss. However, N uptake in the present study was highest when G+N was applied, indicating that this combination can facilitate a timely and adequate supply of N to plants that minimizes the risk of N loss.

Nitrogen recovery efficiency (NRE) provides an understanding of the important process of N uptake under different strategies (Salvagiotti et al., 2009). Increases in NRE in sandy loam soils in the periphery of Amazonia in both years suggested that residue has the potential to mediate nutrients, in particular the availability of N for uptake. We observed a higher NRE in combined use of residue and urea relative to residue alone as it resulted in greater plant N uptake. This suggests that NRE changes considerably under different fertilization strategies, and it can be enhanced in poor quality soils through integration of residue and urea rather than application of residue or urea on its own. Indeed, G+N and A+N had the highest potential to increase the NRE.

One of the biggest challenges on sandy-loam soils is to reach a higher NUE. As was the case for NRE, the NUE was greater when residue was integrated with N, particularly with A+N. These results were consistent with other studies done by Moura et al., (2010) and Garrido et al., (2017). Overall, we achieved an average NUE ranging from 7 to 19 kg kg^{-1} during three years, which was substantially similar to the values reported by Moura et al., (2010) (8-19 kg^{-1}), who compared application of residues and mineral N in the same study region.

Utilizing residues of leguminous trees form has a range of benefits – it maximizes maize production while reducing N losses (Moura et al., 2010; Marques et al., 2017; Abdou et al., 2016), which results in economic savings.

In this research, many integrated treatments of residue and urea led to a higher gross and net income because they minimized the use of costly fertilizer, and increased production relative to residue alone. Again, the G+N and A+N resulted in the highest gross and net income and highest level of production. This shows that G+N or A+N is economically more viable, and hence the small-scale farmers of in the periphery of Amazonia would be better off if they used them. However, the lowest gross and net incomes and the lowest BCR were achieved in the C treatment (control) as a result of very low production.

Conclusion

Residues from leguminous trees in periphery of Amazonia can be utilized as nutrient sources in humid tropic areas. Residues can also reduce the environmental footprint of chemical fertilizers and reduce the costs for cash-constrained smallholder farmers. An integrated application of *Gliricidia sepium* or *Acacia mangium* and urea was most beneficial among all treatments, resulting in the highest maize production while reducing N loss, increasing NUE, and N uptake highest to mineral N management from urea. The increase in maize grain protein in the G+N or A+N combination confirmed those beneficial effects. A addition of G or A residue can reduce the risk of crop failure and the costs for smallholder farmers in the current agriculture system and can increase the return on investment through high gross and net incomes, and a positive benefit cost ratio.

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Table 1 Chemical property of the experimental residues before the study

Characteristics	*Leucaena leucocephala*			*Gliricidia sepium*			*Acacia mangium*		
	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3
Applied biomass (Mg ha^{-1})	2.5	2.9	4.1	10.3	12.7	12.5	8.3	6.7	7.0
Nitrogen (%)	1.2	1.1	1.3	1.0	1.3	1.4	0.4	0.3	0.3
Phosphorus (g kg^{-1})	7.4	7.6	7.3	6.7	6.6	6.5	8.2	8.3	8.1
Potassium (g kg^{-1})	4.8	4.6	4.4	4.1	4.1	4.0	5.2	5.5	5.0
Calcium (g kg^{-1})	0.8	0.6	0.7	0.6	0.5	0.5	0.4	0.7	0.3

Table 2 Effects of residues on the total plant yield (Mg ha^{-1}), grain yield and harvest index in alley cropping system in the Amazon region

Treatments	Total plant yield (Mg ha^{-1})			Grain yield (Mgha^{-1})			Harvest index (%)		
	Year1[a]	Year2[b]	Year3[c]	Year1[a]	Year2[b]	Year3[c]	Year1[a]	Year2[b]	Year3[c]
L	6.1Bc	6.0Bc	7.3Ac	1.2Ac	2.1Ac	2.3Ac	19.6Cd	35.0Ac	31.5Bd
G	6.7ABc	6.1Bc	7.4Ac	2.2Ac	2.3Ac	2.4Ac	32.8Bc	37.7Ac	32.4Bd
A	6.5ABc	6.2Bc	7.1Ac	2.2Ac	2.0Ac	2.3Ac	33.8Ac	32.2Ac	32.4Ad
L+N	7.9Bb	8.0Bb	9.4Ab	3.7Bb	3.9Bb	4.5Ab	46.8Aa	48.7Aa	47.9Aa
G+N	10.5Ba	11.5Aa	12.4Aa	4.5Aa	4.6Aa	4.8Aa	42.7Aab	40.0Ab	39.0Ac
A+N	9.8Ba	9.6Ba	12.8Aa	4.1Ba	4.2Ba	4.7Aa	41.8Ab	43.7Ab	36.7Bc
BS+N	7.6Bb	7.7Bb	9.0Ab	3.5Ab	3.3Ab	4.0Ab	46.0Aa	42.8Bb	44.4Bb
C	4.2Ad	4.1Ad	4.3Ad	0.4Ad	1.1Ad	1.2Ad	9.5Be	26.8Ad	27.9Ae

*Means followed by the same lower-case letters in a column and capital letters on the lines do not differ significantly by the Tukey test ($p < 0.05$). [a] Year 1 - 2015, [b] Year 2 - 2016, [c] Year 3 – 2017. L (*Leucaena leucocephala*), G (*Gliricidia sepium*), A (*Acacia mangium*), N (urea), BS (Bare soil), C (control).

Table 3 Effects of residues on the grain protein and grain oil in alley cropping system in the Amazon region

Treatments	Grain Protein (%)			Grain oil (%)		
	Year 1[a]	Year 2[b]	Year 3[c]	Year 1[a]	Year 2[b]	Year 3[c]
L	1.33 Acd	1.34 Ac	1.44 Abd	3.50 Ab	3.41 Ab	3.43 Ab
G	1.43 Ab	1.45 Ac	1.65 Ab	3.71 Ab	3.72 Aa	3.22 Aab
A	1.54 Ab	1.43 Ac	1.45 Ab	3.81 Ab	3.82 Aa	3.64 Ab
L+N	2.71 Aa	2.80 Aa	2.78 Aa	3.22 Ac	3.10 Ab	3.02 Aa
G+N	3.11 Aa	2.90 Aa	3.24 Aa	2.82 Ad	2.72 Ac	2.77 Ac
A+N	3.02 Aa	2.80 Aa	3.01 Aa	3.01 Ad	3.33 Ab	2.68 Ac
BS+N	2.90 Aa	2.52 Ab	2.76 Aa	3.42 Ae	3.31 Ab	3.00 Aa
C	0.91 Ad	1.02 Ac	1.22 Ad	4.31 Aa	4.11 Aa	3.45 Aa

*Means followed by the same lower-case letters in a column and capital letters on the lines do not differ significantly by the Tukey test ($p < 0.05$). [a] Year 1 - 2015, [b] Year 2 - 2016, [c] Year 3 – 2017. L (*Leucaena leucocephala*), G (*Gliricidia sepium*), A (*Acacia mangium*), N (urea), BS (Bare soil), C (control).

Table 4. Effects of residue in the nitrogen recovery efficiency (NRE) and use efficiency (NUE) in alley cropping system in the Amazon region

Treatments	NRE (kg kg^{-1})			NUE (kg kg^{-1})		
	Year 1^{a}	Year 2^{b}	Year 3^{c}	Year 2^{b}	Year 1^{a}	Year 3^{c}
L	0.13 Ae	0.15 Ac	0.14 Ac	7.22 Ad	7.44 Ad	7.25 Ad
G	0.16 Ad	0.17 Ac	0.15 Ac	6.60 Ad	6.67 Ad	5.89 Ad
A	0.19 Acd	0.18 Ac	0.14 Bc	8.51 Ac	9.30 Ac	9.01 Ac
L+N	0.25 Abc	0.25 Ab	0.26 Ab	13.91 Ab	13.70 Ab	12.7 Ab
G+N	0.27 Bb	0.29 Aab	0.30 Aa	12.61 Ab	12.41 Ab	13.23 Ab
A+N	0.31 Aa	0.31 Aa	0.33 Aa	19.72 Aa	18.31 Aa	19.76 Aa
BS+N	0.22 Ac	0.22 Abc	0.19 Ad	9.41 Ac	9.72 Ac	10.02 Ac
C	-	-		-	-	

*Means followed by the same lower-case letters in a column and capital letters on the lines do not differ significantly by the Tukey test ($p < 0.05$). ^{a} Year 1 - 2015, ^{b} Year 2 - 2016, ^{c} Year 3 – 2017. L (*Leucaena leucocephala*), G (*Gliricidia sepium*), A (*Acacia mangium*), N (urea), BS (Bare soil), C (control).

Table 5 Effects of residues in gross income and net income and benefit cost ratio

Treatments	TC (US$ ha^{-1})	GI (US$ ha^{-1})	NI (US$ ha^{-1})	BCR (US$ ha^{-1})
L	172.80	861.800	689.00	4.95
G	172.80	1506.85	1334.05	8.75
A	178.80	1158.00	979.20	6.50
L+N	1222.30	1665.05	944.50	1.40
G+N	1222.30	1856.25	633.95	1.50
A+N	1225.80	2280.00	1054.20	1.85
BS+N	1185.15	1197.15	115.10	1.00
C	140.35	612.45	472.10	4.25

Average of data for three years (Year 1 - 2015, Year 2 - 2016, Year 3 – 2017). TC total cost, GI gross income, NI net income, BCR benefit cost ratio, US$ U.S. dollar. L (*Leucaena leucocephala*), G (*Gliricidia sepium*), A (*Acacia mangium*), N (urea), BS (Bare soil), C (control).

Fig. 1 Daily maximum and minimum temperatures (Temp) and rainfall growing three years from crop sowing (day 0) to harvesting (day 120).

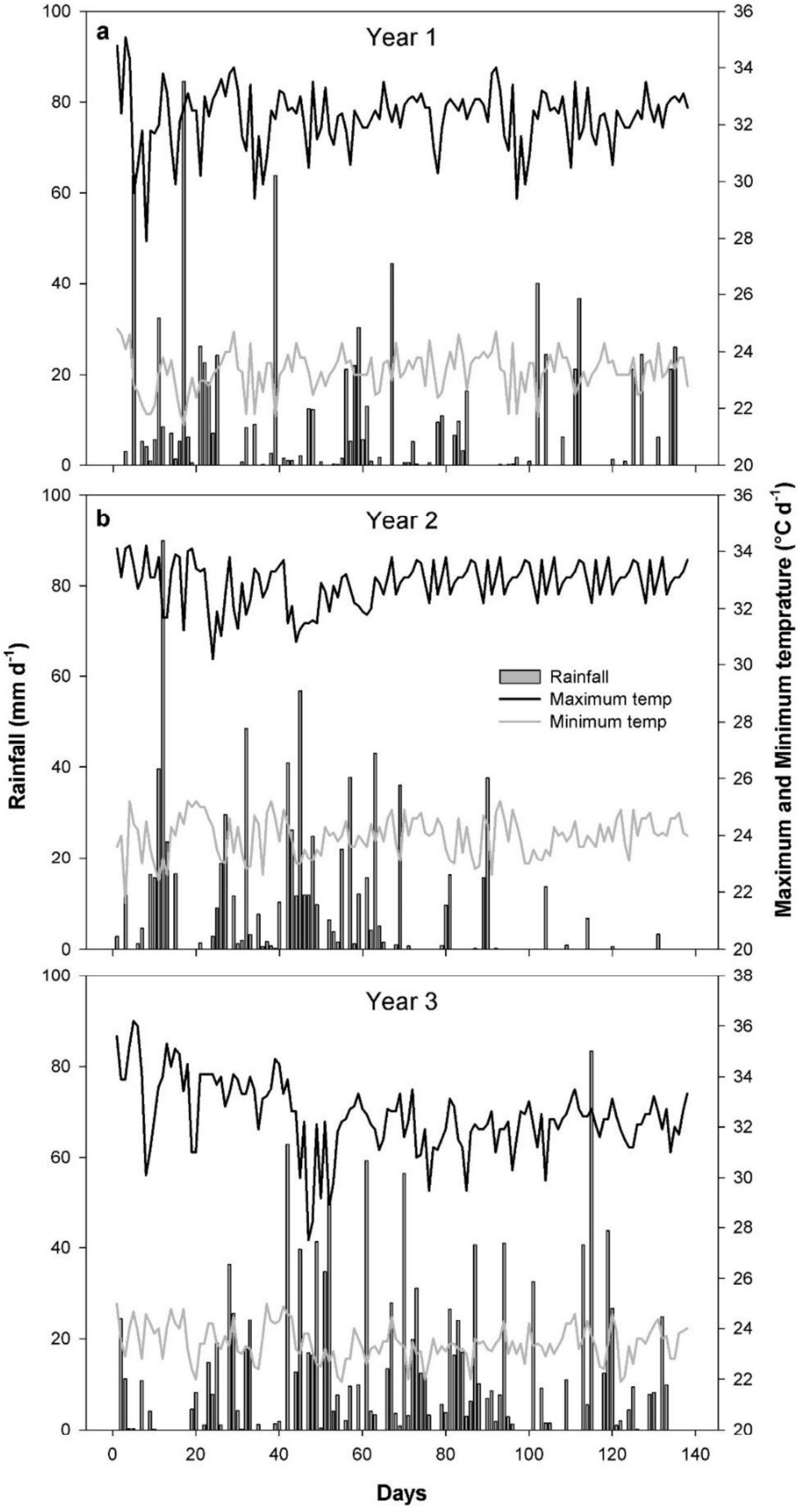


Fig. 2 Relationship between maize N uptake and total plant yield in three years following residue and mineral nitrogen application. Each plotted point represents the mean value of samples taken from replicated (n = 4) plots.

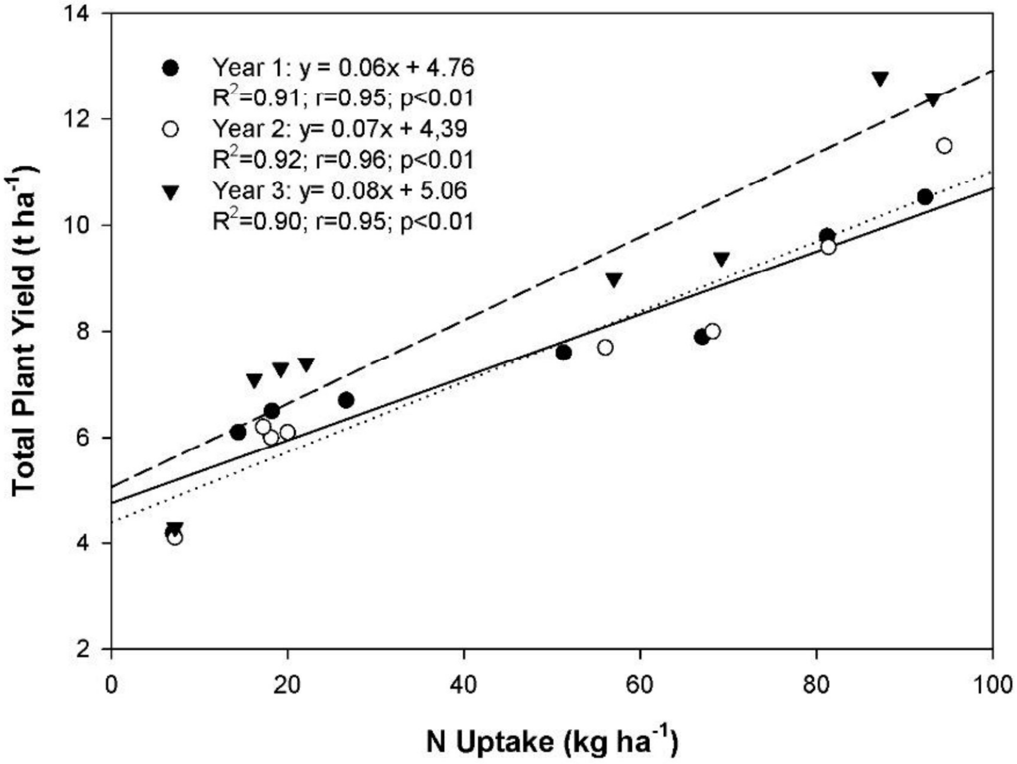


Fig. 3 Relationship between maize N uptake and grain yield in three years following residue and mineral nitrogen application. Each plotted point represents the mean value of samples taken from replicated (n = 4) plots

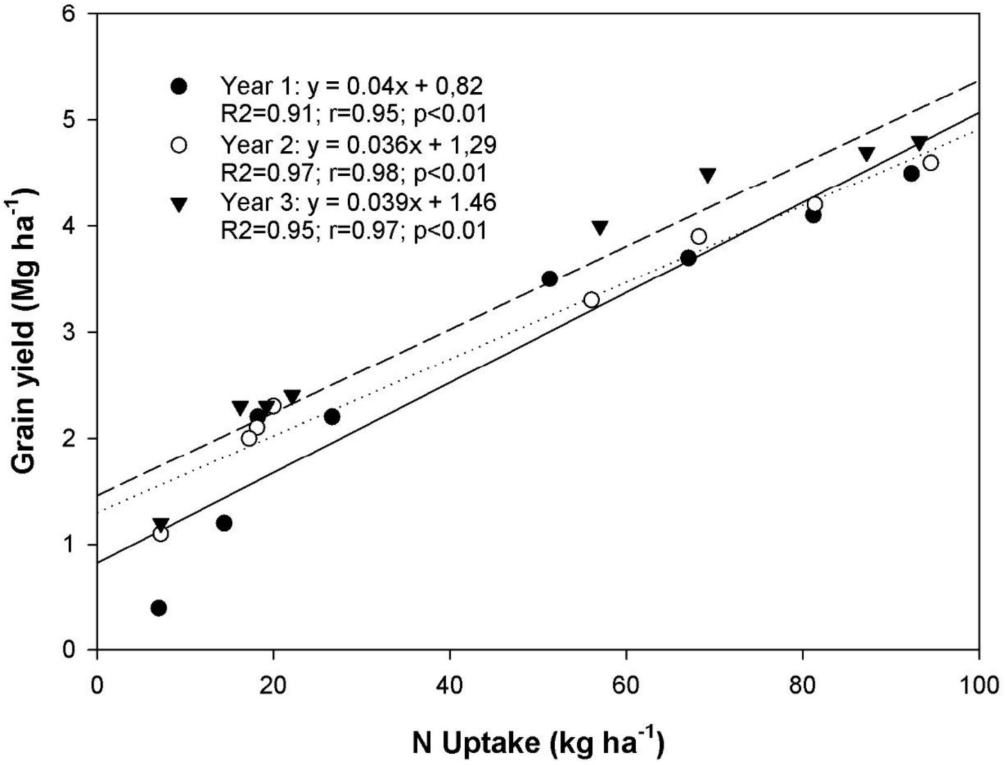


Fig. 4 Effects of residues and integration of residue and chemical nitrogen on the sustainable yield index (SYI)

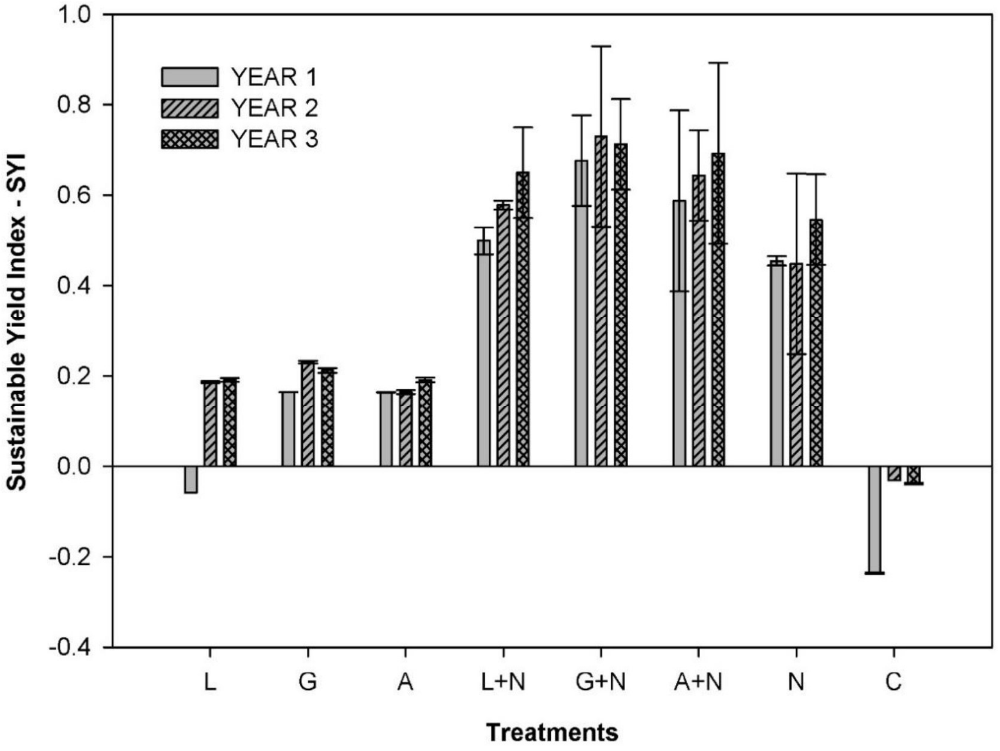


Fig. 5 Relationship between maize N uptake and grain protein in three years following residue and mineral nitrogen application. Each plotted point represents the mean value of samples taken from replicated (n = 4) plots

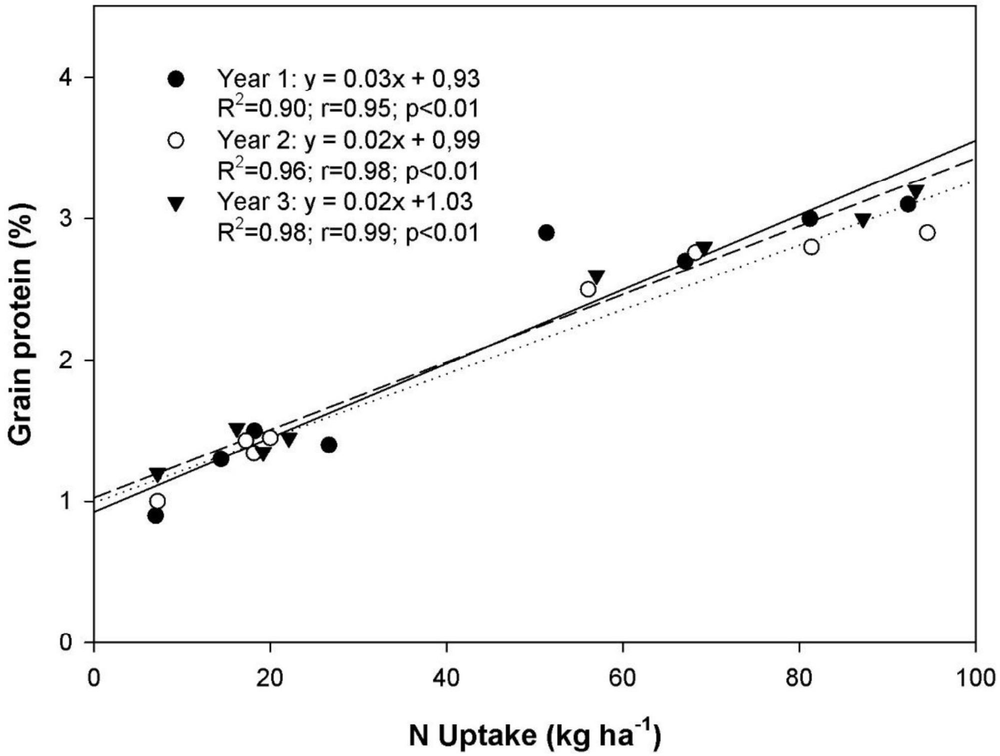


Fig. 6 Relationship between maize N uptake and grain oil in three years following residue and mineral nitrogen application. Each plotted point represents the mean value of samples taken from replicated (n = 4) plots.

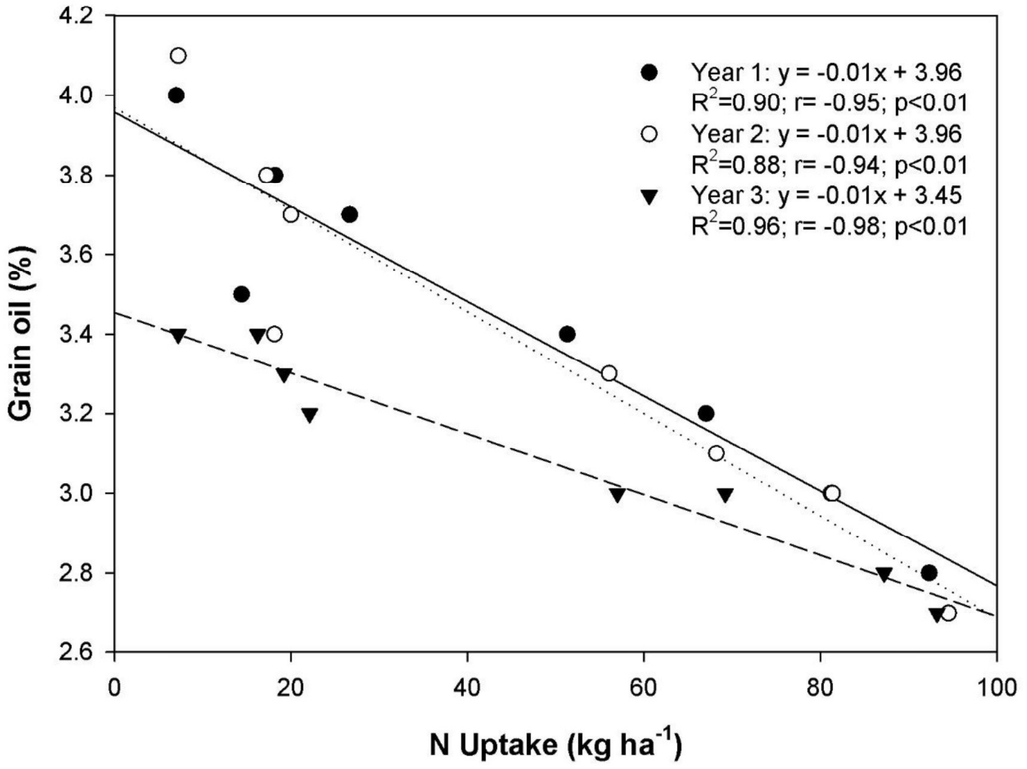


Fig. 7 Maize nitrogen (N) uptake (dark gray portions of bars) versus N vulnerable to losses as volatilization, leaching and denitrification (light gray portions of bars) from the applied N (120 kg ha^{-1}) in the form of residue, and integration of residue and mineral N for growing in three years. Means in a bar not sharing the same letters differ significantly from each other at P<0.05.

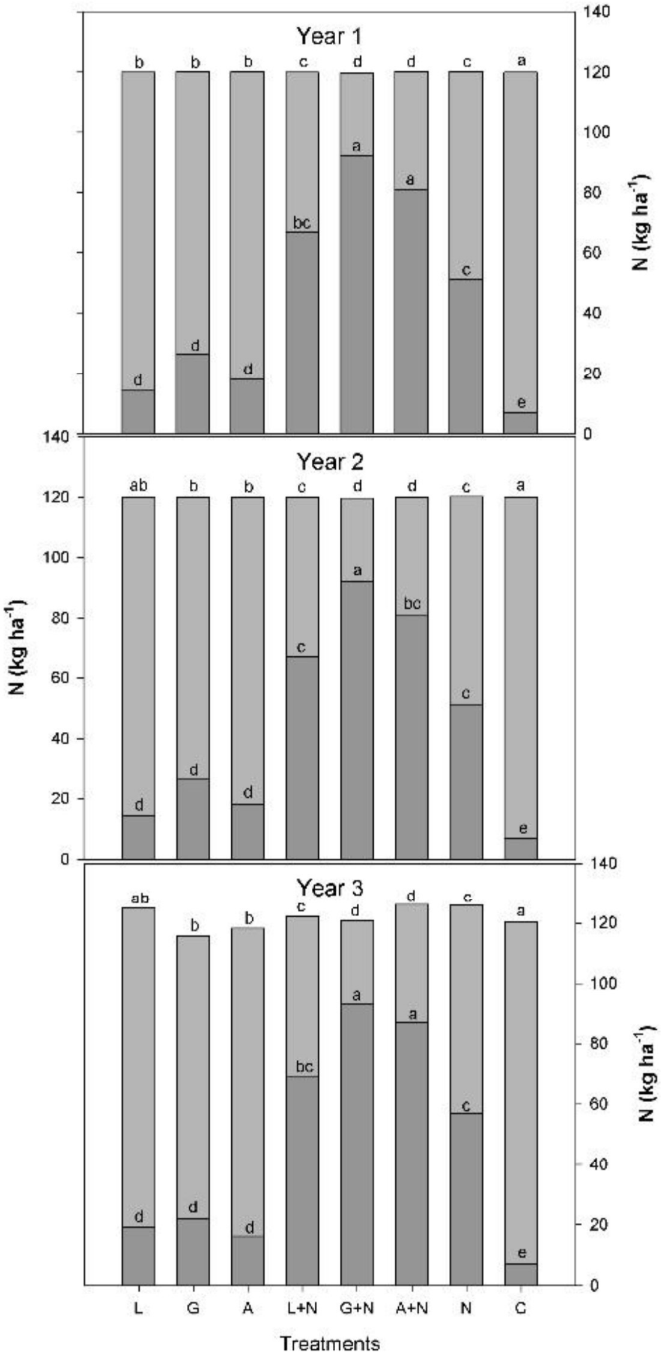
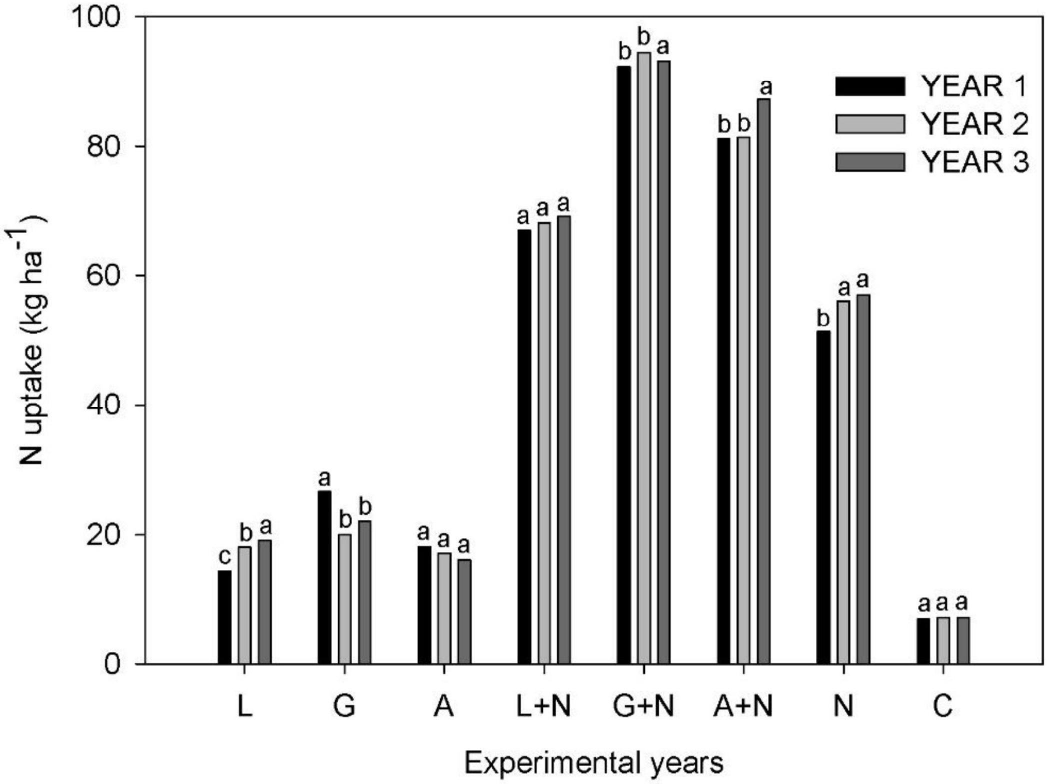


Fig. 8 Variation in maize nitrogen (N) uptake between year in three years. Means in a bar not sharing the same letters differ significantly from each other at P>0.05



☒ Artículo/Article
☐ Nota corta/Short note
☐ Revisión/Revisión
☐ Carta al Editor/Letter to the Editor
☐ In Memoriam

Área de agroecología y desarrollo rural gandero/Area of agroecology and livestock rural development.

Influence of soil cover and N and K fertilization on the quality of QPM maize silage in agroforestry system

Influência da cobertura do solo e adubação com N e K sobre a qualidade da silagem de milho QPM em sistemas agroflorestais

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Alimentação de ruminantes

Summary: In the humid tropics, unfavorable conditions present challenges to smallholder farmers attempting to meet animal nutrition requirement. The objective of this study was to evaluate the influence of soil cover with tree leguminous and N and K fertilization on the quality of QPM maize for silage production. The experimental design consisted of randomized blocks with eight treatments, *Gliricidia sepium* (G), *Leucaena leucocephala* (L), *Acacia mangium* (A), *Gliricidia sepium*+NK (G+NK), *Leucaena leucocephala* +NK (L+NK), *Acacia mangium* +NK (A+NK), bare soil + NK (BS+NK) and control (C) and four repetitions. The grain yield and silage yield of G + NK and

A+NK was significantly higher than that of all other treatments. Treatment with *Leucaena leucocephala* was unable to maintain nutrient levels sufficiently high in the root zone due to low biomass production. The use of N and K in uncovered soil is not feasible under these conditions, whereas in plots covered with tree legumes the use of N and K increases silage yield by approximately 33%.

Resumo: Nos trópicos úmidos, condições desfavoráveis apresentam desafios aos pequenos agricultores que tentam atender às necessidades de nutrição animal. O objetivo deste trabalho foi avaliar a influência da cobertura do solo e da adubação nitrogenada e nitrogenada sobre a qualidade do milho QPM para a produção de silagem. O delineamento experimental foi em blocos casualizados com oito tratamentos, *Gliricidia sepium* (G), *Leucena leucocephala* (L), *Acacia mangium* (A), *Gliricidia sepium* + NK (G + NK), *Leucena leucocephala* + NK (L + NK), *Acacia mangium* + NK (A + NK), solo exposto + NK (BS + NK) e controle (C) e quatro repetições. O rendimento de grãos e o rendimento de silagem de G + NK e A + NK foram significativamente maiores que os demais tratamentos. O tratamento com *Leucaena leucocephala* foi incapaz de manter níveis de nutrientes suficientemente altos na zona radicular, devido à baixa produção de biomassa. O uso de N e K em solo descoberto não é viável nessas condições, enquanto em parcelas cobertas com leguminosas arbóreas o uso de N e K aumenta a produtividade de silagem em aproximadamente 33%.

Introduction

The unsustainable use of the soil of the deforested area at the Amazonian border is one of the greatest threats to the rainforest, mainly for the opening of new areas for the pasture cropping. The forest vegetation after firing, is seen as an easy source of nutrients for pasture. Therefore, the sustainable management of soils with low natural fertility is a major challenge for smallholder agriculture in the humid tropics (Brady, 1996).

The creation of small ruminants in this region has always been an activity of great economic and social importance, since it supplies meat at more affordable prices to rural populations and peripheries of large cities. Despite this, this activity is characterized as low yield, due to the predominance of the type of extensive exploration in most breeding farms, which is influenced by climatic conditions. The presence of two defined climatic seasons, with a dry and one rainy period, degraded pastures and low quality of forage available especially in the dry period, lead to a situation of low productivity, high mortality rate of young animals and late age at slaughter.

Thus, a vicious cycle is established in which poverty increases the pressure on natural resources, and, in turn, the degradation of natural resources increases poverty. In regions on the edge of the Amazon, such as the northeast part of the state of Maranhão, which are agricultural frontier areas where the original vegetation has already been devastated, there now exists an enormous social block represented by a large contingent of farmers who live below the poverty line. It is not a coincidence that many of the poorest towns in Brazil are located in this region, with human development index ranging between 0.498 and 0.467 (Fearsnside, 2002).

Efficiency of Nitrogen and potassium usage is a major factor for successful management of low input agrosystems in soils in the periphery of Amazonia, which are susceptible to cohesion and subject to high nutrient leaching. Unlike other regions of Brazil, the sole use of inorganic potassium (K) and nitrogen (N) fertilizers is not recommended, as this will not allow the crop to reach its potential productivity.

Nutrient retention in the root zone can be enhanced where nutrients are added in slow release forms and biologically mediated processes utilized for nutrient release, as in green manure (Moura et al., 2010). These approaches may be better at sustaining agrosystems in the humid tropics than the saturation of soil solution with soluble nutrients (Drinkwater and Snapp, 2007).

Therefore, the production of corn silage as an alternative food for the dry season is necessary for two reasons: (1) the pressing need to increase food production, and decrease the poverty, and (2) the urgent need to reduce the environmental impacts of burning. Unfortunately, the technological challenges to establishing and maintaining productive and sustainable agricultural systems in this region have not yet been overcome.

Materials and methods

Field experiment

The experiment was performed in an experimental field in Chapadinha, Maranhão, Brazil at 3° 44′ 30″ S and 43° 21′ 37″ W, which is located in the northeast of the country. The region has a hot and semi-humid equatorial climate with a mean precipitation of 2100 mm $year^{-1}$ and two well-defined seasons, a rainy season that extends from January to June and a dry season with a water deficit from July to December.

The soil in the experimental area is an Arenic Hapludult with 200 g kg^{-1} coarse sand, 480 g kg^{-1} fine sand, 70 g kg^{-1} silt and 260 g kg^{-1} clay. The area was limed in January 2013 using a surface application of 1 Mg ha^{-1} of limestone, which corresponded to 279 and 78 kg ha^{-1} of Ca and Mg respectively. Triple superphosphate was applied at 300 kg ha^{-1}, which corresponded to 53.7 kg ha^{-1} of P.

The leguminous trees that were used in the alley cropping system were *Acacia mangium*, *Gliricidia sepium* and *Leucaena leucocephala*. The experimental design consisted of randomized blocks with four replicates, which produced eigth treatments: Gliricidia (G), Leucaena (L), Acacia (A), Leucaena+NK (L+NK), Gliricidia+NK (G+NK), Acacia+NK (A+NK), bare soil (BS) and control (C) treatment. The legumes were sown in 2 m spaces between rows and in 0.5 m spaces between plants, which resulted in 10 m × 2 m plots.

The experiment was conducted under a no-tillage system and the legumes were sown in 2013. The legume plants were pruned every year at a height of 50 cm from the ground, immediately after corn germination, to maximize sunlight exposure in the cropping area. Legume tree pruning biomass was distributed homogeneously throughout all plots of the same treatment, in the following dosage (Mg ha^{-1}): Gliricidia, 10.3; Leucaena, 2.5; Acacia, 8.3, and in 2016 they were distributed in the following dosage (Mg ha^{-1}): Gliricidia, 12.7; Leucaena, 2.9; Acacia, 6.7. The crop area had been in fallow since June 2014 and the maize was planted in 2015 and 2016, between the rows of leguminous plants, variety QPM BR 473.

The plots that received mineral fertilization were fertilized with 60/40 kg ha^{-1} of N/K_2O in the forms of urea/potassium chloride divided into two applications: one at the time of sowing and another at the appearance of the fourth pair of maize leaves.

Yield components determination

At the final harvest or at physiological maturity, the grain yield components were separately assessed in an 8 m^2 area. The weight of the ears, number of grains per ear, yield of the grain, Height of insertion of the first ear, ear length, ear diameter, cob diameter and ear index (relation between number of ears and number of plants per plot), were determined and all values were adjusted according to a moisture level of 145 g kg^{-1}. We determined the 100 grain weight by weighing the grain on a scale with an accuracy of 0.0001 g.

Ensiling Process

Maize plants in each plot was wilted for 18 h before chopping. Were chopped to a theoretical particle size of 15 mm with a two row pull-type forage harvester (John Deere, Moline, IL). After chopping, approximately 10 kg of fresh material were collected in separate plastic and taken to the laboratory to make silage. Individual 500 g fresh mixtures were made for each treatment and placed in a 1-L glass jar, with four jars (mini-silo) per treatment.

The experimental design was a completely randomized design. There were four replicate jars for each treatment, L, A, G, L+NK, A+NK, G+NK, BS+NK and C (total of 32 jars). Mini-silos were fermented for 60 d at room temperature (28°C). Average dry matter (DM) density for silage was 165 kg m^{-3}.

Before ensiling, two 250-g subsamples for each treatment were placed in a paper bag and oven dried at 60°C for 48 h for dry matter determination. Subsamples were ground to pass a 1-mm screen in a Wiley Mill and were later analyzed for pre-ensiling chemical composition.

Chemical analyses

For the analyses, grains of corn were crushed in an analytical mill (A11, IKA, Campinas, Brazil) and sifted in a 20-mesh sieve. Humidity was then standardized to 12% in a forced air circulation oven (TE-393, Tecnal, Piracicaba, Brazil) at 105 ∘C.

At opening, each mini-silo was dumped into an ethanol disinfected plastic container and mixed to uniformity. A 250-g subsample was placed in a plastic 20 by 30 cm embossed vacuum pouch (Viva utile Equipment, Campinas, Brazil), immediately vacuum sealed using a Fast vacuum machine (Prolab Equipment, Campinas, BR), and frozen to −18°C for later analysis of fiber and fermentation characteristics.

Crude protein (CP), ether extract (EE) and ashes were determined according to the methodology recommended by the AOAC (1990). The acid detergent fiber (ADF) and NDF contents were determined by techniques described by Goering and Van Soest (1970) and the non-fiber carbohydrates (NFC) was calculated by the expression: CNF = 100 - (FDN + MM + CP + EE), where NDF is neutral detergent fiber, MM is mineral matter (ashes), CP is crude protein and EE ethereal extract

The pH was measured by weighing 15 g wet sample into 250-mL beaker, adding 200 mL deionized water, stirring, and then measuring using a Prolab G65-1R (Prolab, Campinas, BR).

The main minerals in the maize and silage were extracted with nitric acid/perchloric acid (2:1 v/v) according to the AOAC12 and quantified using an inductively coupled plasma optical emission spectrometer (ES-720, Varian, Walnut Creek, CA, USA) with ICP Expert II software.

Statistical analysis

All statistical analyses were completed using INFOSTAT software (2010). All variables were tested or normality of distribution. We conducted an analysis of variance followed by the Tukey-test at $p<0.05$.

Results

The grain yield of A+NK and G+NK was greater than that of all other treatments in 2015 and 2016 respectively, and two times greater than that of BS+NK, resulting in a statistically significant interaction between legume and fertilization ($P < 0.0001$) (Table 1). The larger grain yield of A+NK and G+NK was caused by the increased ear weight and 100-grain weight. The application of NK to bare soil increased significantly 100-grain weight and Grain yield ($P > 0.0001$). The plots that received the G and A biomass alone were more productive compared with those that only received N and K ($P < 0.0001$). The N and K plots were more productive to the control (Table 1). The biomass of gliricidia and acacia with fertilization increased the index of ear, the addition of leucaena did not influence in the increase of the index of ear.

The results obtained in the evaluations made in the whole plant silage phase (Tables 2 and 3) showed a difference between the treatments with biomass of legumes and biomass + fertilization of N and K, with the exception of the number of leaves. This shows that the fertilization with N and K associated to the addition of biomass influences the height of the plant and diameter of the stem.

There was also a statistically significant difference between treatments with biomass and biomass + fertilization for the variables of dry matter of stalk, dry matter of ear, dry matter of leaves and, consequently, mass of dry matter of shoot (Table 3), these important factors, since they are directly related to total silage production.

The large silage yield of G+NK was caused by the increased ear weight and stem weight. The application of NK to bare soil increased significantly ear yield ($P > 0.0001$). The plots that received the legume biomass alone were more productive compared with those that only received N and K ($P < 0.0001$). The N and K plots were not more productive than the control (Table 2).

The dry matter content of the plant contributes to the conservation of silage by inhibiting the growth of undesirable organisms. The silages presented an average content of 32.7% without difference between them (Table 3). These values are within the range indicated by Tosi (1973) as ideal to ensure adequate fermentation of silage.

The treatments A + NK and G + NK did not statistically differ for the mass of wet grains (Table 3). With an average grain yield of 3.9 Mg ha^{-1}, the treatments with biomass alone (L, G and A) were inferior to the treatment with uncovered soil (BS+NK), which produced on average 3.1 Mg ha^{-1} and superior to the control treatment (C). Among treatments with fertilization, only the L + NK treatment was equal to BS + NK (Table 3).

The HE (Table 4), with a mean of 96.6 cm, was statistically the same for the treatments with fertilization and addition of biomass and differed from the treatments with only addition of biomass. The treatments also differed statistically from one another in ear length, ear diameter and number of ear^{-1} grains, with G + NK and A + NK treatment being higher in all three variables. This fact was probably responsible for the higher productivity of these treatments, since the number of spike-1 grains is an essential component of crop yield (Bortolini et al., 2001).

The chemical composition and nutritional value of bromatological corn silage are shown in Table 5. Analyzing the MS fermentation parameters, pH and NH_3-N%/NT can be seen that significant differences ($P < 0.05$) the treatments. The DM contents of the silages differed ($P < 0.05$) and ranged from 19 to 49%. Larger results were found for G + NK and lower for control and L, G A (Table 5).

Analyzing the pH and N-NH_3%/NT of the silages (Table 5), it is noted that the amplitude of variation was small and the materials are within the normal range indicated in the literature, pH less than 4.4 (Soest, 1994) and N-NH_3%/NT less than 10% (McDonald et al., 1991).

Cell wall components differed significantly among maize silages (Table 5). The treatments L, A, G, BS + NK and C presented silages with lower fiber quality than the others due to the higher ($P < 0.05$) NDF and FDA levels promoted by the higher ($P < 0.05$) and CEL (Table 5), higher stem contributions (Table 3) and lower corn cobs.

A + NK, G + NK and L + NK treatment silage showed higher fiber quality, with lower ($P < 0.05$) NDF and ADF contents from the lower ($P < 0.05$) levels of HEM and CEL (Table 5), lower contribution of stem (Table 3) and greater participation of corn cobs (Table 4).

The LDA results of the silages did not differ ($P > 0.05$) and ranged from 4.4 to 5.4%. The treatment with the highest protein content in the silage was G + NK and A+NK. Neither residues or NK fertilizer alone increased the protein content of the maize in two years of evaluation. However, the protein content of G was higher than that of the treatments without residue in the two years evaluation. Therefore, a comparison of protein contents calculated according to grain productivity showed that G had much higher protein than the BS + NK and C (nearly three times higher) (Table 5).

Variations in the Neutral detergent fiber content were small, although certain treatments showed significant differences, and the highest levels were found for the BS+NK, C and L treatments ($P < 0.0001$) (Table 3). The differences in NDF content were positive and significant between L+NK, G+NK, A+NK compared with the L, G and A treatments ($P < 0.02$). The results of the acid detergent fiber indicate that the different combinations of legumes and addition of urea and potassium chloride (Table 3) did not affect the ADF content (Table 5).

No difference ($P > 0.05$) was observed for OM contents in corn silages, ranging from 96.1 to 96.6% (Table 5), which means that the mineral matter contents did not differ either. However, in the Ca contents, no significant differences were observed, with values varying between 3.8 and 4.0% Ca, but the values of K, P and Mg differed, with higher values in the plots fertilized with residues and potassium (Table 5).

The silages did not differ ($P > 0.05$) for CHOT contents (Table 4), with results ranging from 86.1 to 86.7 %. CNF levels differed ($P < 0.05$) among maize hybrids silages. The treatments G + NK and A + NK presented lower levels (Table 4), due to the greater participation of corn ear (Table 3).

The estimated NDF_d did not differ significantly between silages, with values ranging from 32.2 to 39.4%. However, the estimated DNFD showed significant differences (Table 5). The silages of the treatments G + NK and A + NK had lower levels ($P < 0.05$). The fiber quality of G + NK and A + NK silages was higher, as they presented lower NDF content and higher DNFD.

The DIVMS and NDT results showed differences ($P < 0.05$) and followed the same trend behavior as the DFDN (Table 4). The silages of A + NK and G + NK showed higher coefficients of IVDMD and NDT contents. In addition, these results also have relation with the participation of ear in the ensiled biomass (Table 3) and FDA (Table 5).

Discussion

The large differences in yield and protein content between treatments in this experiment showed that suitable crop management may simultaneously increase the quantity and quality of silage maize. The results of this experiment show that in bare soil prone to cohesion the use of N and K in uncovered soil is not feasible, whereas in covered plots the use of N and K increases silage maize productivity by approximately 33% compared with BS+NK.

The differences in the yield of protein between the treatments G+NK and BS+NK can be accounted for by the increased uptake of nutrients in the plots with residues. Loss of N fertilizer in cereal production can be attributed to the combined effects of denitrification, volatilization and leaching. The uptake of N by crops is closely related to rootability conditions in the soil: higher root length densities lead to higher NO_3 uptake and less leaching (Garnett et al., 2009). When fertilizers are applied, as urea, to the surface without incorporation as in no-till systems, N losses can exceed 40%, and these losses are generally greater with increasing temperature, soil pH and surface residues (Raun et al., 1999). Therefore, for cereal crops grown under tropical conditions, the steady release of N from organic sources during the crop cycle, including the post-flowering stage, is important in complementing early and rapid availability of N from synthetic fertilizers.

The large differences in silage yield between treatments in this experiment showed that the use of N and K with G*liricidia sepium* increases silage maize productivity by approximately 15% compared with

In most tropical soils with a small buffering capacity in which K+ ions do not interact strongly with the soil matrix, the application of K fertilizers results in a higher K+ concentration in the soil solution that then may be leached under tropical humid conditions (Kolahchi and Jalali, 2007). Because of the weak bond between K+ ions and soil BS+NK. Moura et al. (2015) Found in treatments with G*liricidia sepium* higher concentrations of carbon stock in the litter, free light fraction (FLF) and total organic C relative to the control. These increased fractions are important for the soil environment because they enhance soil rootability, improve the fauna's habitat and increase the absorption the N and K constituents, a reduction in the K concentration may also occur by the replacement with other cations, especially calcium after liming. K uptake is highly dependent on the root development and requires root systems with vigorous growth to intercept and absorb available K (Sawyer, 2002). The response to the K supply at the final stage of cereal development suggests that the constant availability of K must be carefully considered to increase the productivity and sustainability of cropping systems under humid tropical conditions (Moura et al., 2010).

The treatments L, G and A, presented lower yield and quality of silage. The inability of green manure to maintain sufficiently high nutrient levels in the root zone because of the low concentrations of these elements in legume residues suggests that a replacement strategy using mineral fertilizers must be adopted to increase their concentrations in the soil during critical stages (Aguiar et al., 2010).

Another important advantage of the no till alley cropping system is related to reducing the need for external nutrient input since it facilitates the development of mineral reserves, mainly due to high amount of calcium, nitrogen and potassium recycled. Thus, it contributes to an enhanced sustainability of the system, by recycling nutrients from the deeper to the upper layers. In our experiment, more significant amounts of N and K were recycled by G + NK than by other treatments.

The most efficient treatment was G+NK due to high quantity of biomass produced by Gliricidia and high concentrations of N and K contained in residues. Furthermore, alley cropping produced a higher quantity of N than required for a corn crop, particularly in the Gliricidia where more than 220 kg ha^{-1} year^{-1} of N was applied.

The DM contents of the silages differed and ranged from 19 to 49%. Larger results were found for G + NK and lower for control and L, G A. These differences are mainly due to the corn cycle in each treatment that define a greater or lesser contribution of spike in the biomass DM (Table 4), because according to Nussio (1995), early hybrids present higher DM content in the plant when reaching the point of grains for silage.

According to the literature, the indicated DM content for the production of corn silage has generally been 30 to 35%. However, Nussio (1995) indicated the range of 33 to 37% and Zago (1991), obtained the best results between production, digestibility and voluntary consumption in the range of 37 to 43% DM.

One of the parameters used to assess the quality fermentation of the silage is the pH. The pH values found for the hybrid silage evaluated were similar (Table 5), and are all within the limits for classification of good quality silage. The mean value observed in silages of different maize hybrids was 3.8. According to Muck and Shinners (2001), silages that underwent appropriate fermentation had pH values between 3.8 and 4.2. No silage had pH higher than 4.2, what would classify them as good fermentative quality. Soest (1994) reports that in silages with a high MS content, humidity less than 65%, pH becomes a parameter of little importance, since the development acid-producing microorganisms is inhibited by water deficiency and high osmotic pressure. Therefore, it is observed that even with an MS content of more than 35%, the silages in this study had very good pH values, which can be explained by the high sugar/protein ratios, normally present in the corn crop, which promote lactic acid production and lower degradation of the protein to ammonia. Kung and Shaver (2001) mentioned that for the fermentation process to be compromised and the pH values to be high (pH> 4.4), it is necessary that the DM of the ensiled forage is higher than 50%. Thus, the levels found in this study (19.23 to 45.09% MS) are within the normal range.

According to Soest (1967) values of NDF above 60% have negative correlation with the consumption of MS and according to Cruz and Pereira Filho (2001), the ideal level of NDF should be around 50%. The contents of the fibrous fraction in the corn silages varied greatly, which can be explained by the differences found in the stem yield (Table 3). According to Nussio (1995), the quality of stem fiber is due to characteristics of differentiated agronomic behavior, where histological cuts of the same demonstrate cells of different sizes, resulting from genetic improvement programs to increase the resistance of the stem to lodging and to agents pathogenic.

NDF values higher than those obtained in this study were reported by Neumann et al. (2000): 62.34 to 68.65%. On the other hand, the levels of CEL and LDA were similar to those obtained by the same author: 23.22 to 27.92% and 4.53 to 5.44% for CEL and LDA respectively.

The addition of potassium chloride to the soil as a source of K significantly influence the levels of this mineral in the corn silage, especially in treatments that had soil cover. The only mineral element that presented levels above 1% in DM was potassium, in the treatments with residues and NK, proving the necessity of the correct base fertilization for this element, when the area for corn cultivation is successively used for the production of silage, in order to avoid exhaustion of potassium in soil.

The higher DM content of the treatments A + NK and G + NK did not interfere in the digestibility of their silage (Table 5), and it was possible to obtain good DM production per area combined with a good nutritive value. According to National (1989), silages with high grain percentages would show NDT of 70%, while in those with low NDT would be of 60%, which was proven in this study, because the silages that presented greater participation of corn cobs showed NDT just over 70% and those who had a lower share of corn cob NDT was close to 60%.

Conclusion

Our experiment showed that the use of waste alone or fertilizers alone does not increase corn silage productivity. Fertilization with N and K in plots with residues increases silage up to 33%. The treatment with the highest silage production was G + NK.

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Table 1. Yield components in experimental treatments of QPM BR 473 maize in 2015 and 2016 in an agroforestry system in the periphery of the Amazon, Brazil. *Tabela 1. Componentes da produtividade dos tratamentos experimentais do milho QPM BR 473 em 2015 e 2016, em um sistema agroflorestal na periferia da Amazônia, Brasil.*

Component	L	G	A	L+NK	G+NK	A+NK	BS+NK	C
				2015				
HG	24.3b	23.1b	22.3b	26.0ab	30.1a	29.3a	24.4b	19.0c
WE	48.2d	90.2b	80.4c	88.0b	124.0a	122.0a	49.2d	38.5e
GY	1.4e	2.2d	2.1d	2.8bc	4.7a	4.7a	2.6c	0.9f
FPP	23.5b	27.7ab	30.2a	28.5a	29.6a	30.4a	25.2b	17.2c
EI	0.99b	0.98b	0.97b	0.95c	1.33ab	1.45a	0.98b	0.89d
				2016				
HG	33.2bc	30.1c	32 bc	35.8b	40.2a	39.4a	27.7c	23.3d
WE	67.4d	81.5c	85.0c	91.5b	147.8a	145.8a	68.7d	45.5e
GY	1.6d	2.1c	2.2c	2.9b	4.6a	4.9a	2.9b	0.7c
FPP	21.6b	27.7ab	32.2a	26.6b	30.6a	31.3a	25.2b	16.2c
EI	0.99b	0.98b	0.97b	0.95b	1.33ab	1.45a	0.98b	0.89c

Different letters in the same row indicate significant differences by the Tukey-test ($P < 0.05$). N, nitrogen; K, potassium; BS, bare soil; L, Leucaena; G, Gliricidia; A, Acacia; C, control. HG, Hundred-grain weight (g); WE, Weight of ear (g); GY, Grain yield (Mg ha^{-1}); FPP, Final population of plants (plants ha^{-1}); EI, Ear index

Letras diferentes na mesma linha indicam diferenças significativas pelo teste de Tukey ($P < 0,05$). N, nitrogênio; K, potássio; BS, solo descoberto; L, Leucaena; G, Gliricidia; A, acácia; C, controle. HG, Peso de cem grãos (g); WE, Peso da espiga (g); GY, rendimento de grãos (Mg ha^{-1}); FPP, População final de plantas (plantas ha^{-1}); EI, índice de espiga

Table 2. Averages of vegetative variables of maize: plant height (HP), stem diameter (DS) and number of leaves (NL) of different treatments in 2015 and 2016 in an agroforestry system in the periphery of the Amazon, Brazil. *Tabela 2. Médias das variáveis vegetativas do milho: altura da planta (HP), diâmetro do caule (DS) e número de folhas (NL) dos diferentes tratamentos em 2015 e 2016 em um sistema agroflorestal na periferia da Amazônia, Brasil.*

Agronomic characteristics	L	G	A	L+NK	G+NK	A+NK	BS+NK	C
					2015			
Plant height (m)	1.35c	1.32c	1.39c	1.86a	1.85a	1.89a	1.49b	1.20d
Number of leaves	14.3a	14.2a	14.2a	14.6a	14.6a	14.5a	14a	12b
Stem diameter (mm)	14.2c	15.3c	15.1c	22.1ab	25.1a	24.4a	21.0b	10.1d
					2016			
Plant weight	1.41c	1.43c	1.40c	1.89a	1.82a	1.82a	1.61b	1.19d
Number of leaves	14.1a	14.5a	14.2a	14.8a	14.7a	14.6a	14.2a	12.1b
Stem diameter	12.4c	13.1c	14.2c	22.6ab	24.3a	23.4a	19.1b	10.0d

Different letters in the same row indicate significant differences by Tukey's test ($P < 0.05$). N, nitrogen; K, potassium; BS, bare soil; L, Leucaena; G, Gliricidia; A, Acacia; C, control.

Letras diferentes na mesma linha indicam diferenças significativas pelo teste de Tukey (P <0,05). N, nitrogênio; K, potássio; BS, solo descoberto; L, Leucaena; G, Gliricidia; A, acácia; C, controle.

Table 3. Average dry matter mass of steam (DMS), dry matter mass of ear (DME), dry matter mass of leaves (DML), mass of dry matter of aerial part (DMAP), grain mass with 35% humidity (GM).

Tabela 3. Média da matéria seca dos colmos (DMS), matéria seca da espiga (DME), matéria seca de folhas (DML), massa de matéria seca da parte aérea (DMAP), massa de grãos com 35% de umidade (GM).

	L	G	A	L+NK	G+NK	A+NK	BS+NK	C
					2015			
DMS (g plant^{-1})	52.1c	55.1c	58.2bc	61.3b	72.4a	60.1b	60.2b	43.1d
DME (g plant^{-1})	84.3d	84.2d	84.2d	91.6b	98.6a	87.5b	84.0c	70.0e
DML (g plant^{-1})	24.2c	26.3c	26.1c	36.1a	38.1a	37.4a	28.0b	16.1d
DMAP (Mg ha^{-1})	4.2c	4.6c	4.9c	5.1ab	7.2a	9.2a	5.8b	3.2c
GM (Mg ha^{-1})	1.8e	2.3d	2.3d	2.7c	4.9 a	5.4 a	3.6b	1.5e
					2016			
DMS (g plant^{-1})	53.3c	54.7c	55.2c	58.6b	67.1a	59.1b	60.1b	44.1d
DME (g plant^{-1})	82.3c	85.2bc	83.2c	90.6b	97.6a	89.6b	86.0b	71.0d
DML (g plant^{-1})	22.4c	23.1c	24.2c	22.6a	24.3a	23.4a	19.1b	14.0d
DMAP(Mg ha^{-1})	3.4cd	4.1c	4.2c	5.1b	8.4a	8.2a	5.7b	2.6d
GM (Mg ha^{-1})	1.7de	2.4c	2.4c	3.0 b	5.3 a	5.5 a	3.4 b	1.1 e

Different letters in the same row indicate significant differences by Tukey's test ($P < 0.05$). N, nitrogen; K, potassium; BS, bare soil; L, Leucaena; G, Gliricidia; A, Acacia; C, control. *Letras diferentes na mesma linha indicam diferenças significativas pelo teste de Tukey (P <0,05). N, nitrogênio; K, potássio; BS, solo descoberto; L, Leucaena; G, Gliricidia; A, acácia; C, controle.*

Table 4. Averages of the ear height (HE), ear length (LE), Ear diameter (DE), Number of grain ear^{-1} (EGN), Cob diameter (DC). *Tabela 4. Médias da altura da espiga (HE), comprimento da espiga (LE), diâmetro da espiga (DE), número de grãos por espiga^{-1} (NGE), diâmetro da espiga (DC)*

	L	G	A	L+NK	G+NK	A+NK	BS+NK	C
				2015				
HE (cm)	64.3c	62.2c	64.2c	95.6a	96.6a	98.5a	74b	52d
LE (cm)	12.2cd	16.3b	15.1c	16.9b	19.1a	19.4a	12.0d	10.1e
ED (cm)	36.6c	37.2c	37.0c	40.2b	46.1a	47.1a	40.2b	29.7d
EGN	198.3d	377.4c	379.5c	399.4b	471.9a	470.3a	391.6b	207.1d
DC (mm)	24.2a	25.0a	25.9a	27.2a	27.6a	27.9a	20.0a	18.2b
				2016				
HE (cm)	66.1c	65.6c	61.0c	97.6a	99.1a	96.3a	78b	57d
LE (cm)	12.1cd	16.2b	15.3c	16.7b	19.7a	19.5a	12.6d	10.4e
ED (cm)	36.3c	37.2c	37.4c	40.1b	46.6a	47.7a	40.6b	28.7d
EGN	199.0d	270.8b	265.0b	262.8b	367.9a	366.1a	204.1c	198.3d
DC (mm)	23.5a	24.1a	24.3a	25.2a	27.8a	24.1a	23.2a	18.2b

Different letters in the same row indicate significant differences by Tukey's test ($P < 0.05$). N, nitrogen; K, potassium; BS, bare soil; L, Leucaena; G, Gliricidia; A, Acacia; C, control. *Letras diferentes na mesma linha indicam diferenças significativas pelo teste de Tukey (P <0,05). N, nitrogênio; K, potássio; BS, solo descoberto; L, Leucaena; G, Gliricidia; A, acácia; C, controle.*

Table 5. Chemical and bromatological composition of maize silages, as the contents of dry matter (DM), organic matter (OM), crude protein (CP), neutral detergent insoluble fiber (NDF), hemicellulose (HEM), acid detergent insoluble fiber (FDA), total carbohydrates (CHOT), non-fibrous carbohydrates (NFC), digestible NDF (NDFd), NDF digestibility (DNDF), in vitro dry matter digestibility (IVDMD), total digestible nutrients (NDT), calcium (Ca), phosphorus (P), potassium (K), magnesium (Mg). *Composição química e bromatológica de silagens de milho, como os teores de matéria seca (MS), matéria orgânica (MO), proteína bruta (PB), fibra insolúvel em detergente neutro (FDN), hemicelulose (HEM), fibra insolúvel em detergente ácido (FDA), carboidratos totais (CHOT), carboidratos não fibrosos (CNF), digestibilidade in vitro da matéria seca (FDNi), digestibilidade in vitro (FDN), digestibilidade in vitro da matéria seca (DIVMS), nutrientes digestíveis totais (TND), cálcio (Ca), fósforo (P), potássio (K), magnésio (Mg).*

	Silage corns*							
Variables	L	G	A	L+NK	G+NK	A+NK	BS+NK	C
	------------------------------Fermentation Parameters------------------------------							
Ph	3.8 a	3.8 a	3.8 a	3.9 a	4.0 a	4.0 a	3.8 a	3.8 a
DM (%)	29 c	33 c	33 c	40 b	42 a	45 a	39 b	19 d
N-NH$_3$%/NT	2.7 c	2.6 c	2.7 c	3.1 b	3.6 a	3.7 a	3.3 b	2.1 e
	-----------------------------Cell wall components (% in DM)--------------------							
NDF	60.2a	58.3a	57.1a	49.2b	48.2c	48.3c	55.1b	60.5a
ADF	39.2a	42.7a	44.1a	34.2b	29.1c	29.3c	40.4a	40.1a
HEM	30.1 a	29.8 a	29.4a	21.3b	22.3 b	22.5 b	28.5a	27.1a
CEL	27.4 a	28.3 a	28.0a	24.0 b	24.3 b	24.2 b	25.7 b	20.1c
LDA	4.4 a	4.4 a	4.5 a	5.1 a	5.3 a	5.4 a	5.3 a	4.9 a
	----------------------------Parameters qualitatives (% in DM)--------------------							
OM	96.1 a	96.1 a	96.7 a	96.4 a	96.6 a	96.6 a	96.5 a	96.4a
CP	1.2d	4.0c	1.9d	5.6b	6.9a	5.9b	2.0d	1.2d
EE	3.5 b	3.3 b	3.5 b	4.2 a	4.5 a	4.5 a	4.3 a	3.5b
CHOT	87.1 a	87.4 a	87.6 a	87.2 a	87.4 a	87.5 a	87.0 a	87.3a
NFC	33.2 a	33.4 a	33.1 a	33.4 a	24.6 b	25.5 b	33.2 a	33.2a
NDF$_d$	39.2 a	39.3 a	39.4 a	37.9 a	33.2 a	33.4 a	39.2 a	39.4a
DNDF	59.9 c	54.6 b	54.7 b	54.4 a	78.8 a	78.3 a	59.6 c	59.7c
IVDMD	52.3 b	53.3 b	54.3 b	54.3 b	67.4 a	67.7 a	66.7 a	51.2b
NDT	60.2 b	60.4 b	62.0 b	62.3 b	71.2 a	71.4 a	62.2 b	59.5b
	-----------------------------Mineral composition (% in DM)----------------------							
Ca	0.8 b	0.8 b	0.8 b	0.13 a	0.14 a	0.15 a	0.10 b	0.10b
P	0.09 c	0.3 b	0.5 b	0.7 a	0.6 a	0.6 a	0.6 a	0.06c
K	0.76 c	0.75 c	0.72 c	1.03 a	1.05 a	1.03 a	0.87 b	0.77c
Mg	0.12 c	0.10 b	0.10 b	0.13 b	0.23 a	0.24 a	0.23 c	0.01c

* The values correspond to the average of 4 replications per year. Different letters in the same row indicate significant differences by Tukey's test (P <0.05). N, nitrogen; K, potassium; BS, bare soil; L, Leucaena; G, Gliricidia; A, Acacia; C, control. DM, Dry matter (Mg ha^{-1}); CP, Crude protein (%); NDF, Neutral detergent fiber; ADF, Acid detergent fiber; P, Fósforo (g kg^{-1}); N, Nitrogen (g kg^{-1}). Letras diferentes na mesma linha indicam diferenças significativas pelo teste de Tukey (P <0,05). N, nitrogênio; K, potássio; BS, solo descoberto; L, Leucaena; G, Gliricidia; A, acácia; C, controle. DM, Matéria seca (Mg ha^{-1}); CP, Proteína bruta (%); NDF, fibra detergente neutra; ADF, fibra de detergente ácido; P, Fósforo (g kg^{-1}); N, nitrogênio (g kg^{-1})

Carbon storage in alley cropping system with leguminous trees in the humid tropics of Brazil

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Abstract: Alley cropping system play an important role in sequestering carbon (C). The objectives of this study were to quantify and compare the carbon stocks in tree biomass above- and below-ground in system alleys with *Gliricidia sepium, Leucaena leucochephala, Clitoria fairchildiana* and *Acacia mangium*. The methodology included a randomized block design with five plots and 8 repetitions. It was made destructive sampling of 4 trees per plot (one of each species), measuring for each tree diameter at breast height (DBH), stem height, total tree height, branch weight, leaf weight and root gross weight. A logarithmic model was developed to quantify the woody biomass below ground. The total carbon stored in system was 207.3 Mg C ha^{-1}, with the *G. sepium* trees contributing 25.80 % of the total C (45.2 Mg C ha^{-1}), the *L. leucocephala* trees contributing 23.15 % of the total C (39.04 Mg C ha^{-1}), the *C. fairchildiana* trees contributing 19.63 % of the total C (31.68 Mg C ha^{-1}), *A. mangium* trees contributing 30.91 % of the total C (53.06 Mg C ha^{-1}) and control contributing 0.44 % of the total C. The litter stored 30.9 Mg C ha^{-1}year^{-1}, with the *G. sepium* trees contributing 6.8 Mg C ha^{-1}, *L. leucocephala* contributing 7.3 Mg C ha^{-1}, *C. fairchildiana* trees contributing 7.5 Mg C ha^{-1}, and *A. mangium* trees contributing 9.3 Mg C ha^{-1}.

Keywords: Carbon sequestration, alley cropping systems, litter, woody biomass.

Introduction

The increase in the atmospheric concentration of carbon dioxide (CO_2) is the principal cause of global climate change (Montagnini and Nair 2004; Kaonga and Bayliss-Smith 2009). The most recent measurements confirm the expectations that atmospheric CO_2 concentration exceed the 410 ppm threshold in 2018 (http://www.esrl.noaa.gov/gmd/ccgg/trends/weekly.html). It is estimated that agriculture accounts for about 25% of the CO_2, 50% of the CH_4, and 70% of the N_2O emitted on a global scale through anthropogenic sources (Hutchinson et al. 2007).

The prevailing form of agricultural management in the Amazon border region, including many parts of Brazil, is low-yield shifting cultivation, where vegetation is slashed and burned to make way for crops. This land use results in a short-lived production because of the rapid depletion of soil nutrients, and also negatively affects biodiversity and contributes to global warming (Fearnside 2002).

Alley cropping system could offer a viable opportunity to deal with climate change issues, having the potential to sequester and store atmospheric CO_2 over long periods (Albrecht and Kandji 2003; Lorenz and Lal 2014). In ustainable-managed agroforestry systems, a large portion of organic C returns to the soil in the form of crop residues and tree litter (Oelbermann et al. 2004). Those inputs can help to stabilize soil organic matter (SOM) and decrease biomass decomposition rate and SOM destabilization, improving SOC stocks (Young 1997; Oelbermann et al. 2004; Lal 2004; Sollins et al. 2007).

The transformation of the original forest into various types of agroforests systems results in a smaller decrease in C stocks than the transformation of forests into cropland, pastures or degraded grasslands. After burning and cropping for an average of 2 years, about 80% the C stock is lost (Sanchez et al. 2000). In contrast, agroforests established immediately after slash and burn by planting trees along with food crops regained 35% of the original carbon stock of the forest. Through the establishment of tree-based systems in degraded pastures, croplands, and grasslands, the time-averaged C stocks in the vegetation increases by 50 Mg C per ha in 20–25 years, while that in the soil increases by 7 Mg C per ha (Palm et al. 2004).

The different tree species lead us to inquire, first, about their importance as carbon reservoirs in alley cropping systems, about the relative importance of their associated biomass, litterfall and residues corn in carbon flows. Although alley cropping system are expanding gradually in the Amazon frontier region, information on its potential to capture and store C are scarce. The aim of the present study was to quantify organic C stocks in the above-and belowground tree biomass and in the soil in alley cropping system with different tree species.

Material and methods

Study area

The experiment was performed in an experimental field in Chapadinha, Maranhão, Brazil at 3° 44′ 30″ S and 43° 21′ 37″ W, which is located in the northeast of the country. The region has a hot and semi-humid equatorial climate with a mean precipitation of 2100 mm year^{-1} and two well-defined seasons, a rainy season that extends from January to June and a dry season with a water deficit from July to December (Fig 1).

Experimental plots

To study C pools, an alley cropping system was used with four tree species. The experimental design was randomized blocks, with five treatments: *L. leucocephala*, *G. sepium*, *C. fairchildiana*, *A. mangium*, control and eight replicates. Each plot had an area of 40 m^2 (10 m length 4 m width). The soil in the experimental area is an Arenic Hapludult with 189 g kg^{-1} coarse sand, 420 g kg^{-1} fine sand, 66 g kg^{-1} silt and 230 g kg^{-1} clay. The area was limed in January 2009 using a surface application of 1 Mg ha^{-1} of limestone, which corresponded to 279 and 78 kg ha^{-1} of Ca and Mg respectively. Triple superphosphate was applied at 300 kg ha^{-1}, which corresponded to 53.7 kg ha^{-1} of P. The main characteristics of system are described in Table 1.

Sampling of trees and litter

To determine the tree biomass, 300 trees of each species were selected from the forty plots. For each individual tree, breast-height diameter (DBH) was measured using a diametric tape at a height of 1.3 m. To obtain a destructive sample of tree biomass (above- and below-ground), 32 trees were selected (ten trees of DBH < 5 cm, ten with 5 > DBH < 15 cm and twelve with DBH > 15 cm). These 32 trees were cut down, and their coarse roots (≥10 mm) were unearthed. For each tree, the green weights of the stem, branches, leaves and coarse roots were determined. Then, dry matter (DM) and C content were measured in the laboratory.

To determine the C flows in the litter was using a collector commonly used to estimate DM production in pastures (Morley, 1964), a jig - a detachable accessory, made of wood in the same dimensions of 0.40 x 0.40 m. The accumulation of litter was collected every 30 days, including all plant material (leaves, seeds, flowers, bark and branches ≤ 5 cm diameter).

Both the tree and litter biomasses were weighed in situ using a portable electronic scale to determine the fresh weight. To determine the DM 1 kg samples were taken from the litter and tree components (i.e., leaves, branches, stem and coarse roots). These were then dried in a forced-air circulation oven at 65 ºC until achieving constant weight.

Soil samples

Soil samples were collected from within each plot for each treatment. One soil sample from each depth range (0–10 cm, 10.1–20 cm and 20.1–30 cm) was extracted from 30 x 30 x 30 cm trial pits. At each depth, the soil bulk density was measured using the cylinder method (Page-Dumroese et al. 1999). The soil samples were deposited into labelled plastic containers. Once sampling was complete, soil from each depth and sub-plot was mixed until attaining a uniform color, and a sub-sample of approximately 500 g was collected. Subsequently, the samples were dried in the shade at environmental temperature and then passed through a 2 mm sieve to determine the organic matter (OM) and C content.

Biomass quantification

To quantify the total biomass of the tree (above ground) were pruning all system trees and heavy then. To quantify the total tree biomass (below-ground) (Mg ha^{-1}), a logarithmic model (see below) was constructed, for each species, using the DBH data from the 160 sampled trees. This method was developed using the models proposed by Segura and Kanninen (2005), Gómez et al. (2010) and Picard et al. (2012). The models included the variables DBH, total biomass and coarse root biomass and were implemented using SAS statistical analysis software (SAS 2012). The efficiency, measured based on the efficiency coefficient of the Nash–Sutcliffe model (NSE) and mean coefficient of determination (R^2) were used to identify the best model. Once the model was validated, adjustments were made using the data from all 160 trees. Subsequently, the biomass of the 160 trees was determined from their DBH by the following allometric equation:

$$Tree\,biomass = EXP\,(a + b * DBH + c * DBH^2 + d * DBH^3)\ (1)$$

Where, *Tree biomass* total dry biomass (Mg), *EXP* exponential function, *DBH* diameter at breast height, and *a, b, c* and *d* model parameters.

The tree biomass per meter was first estimated along the row of the plots using the biomass per tree data. Subsequently, the length of the row for one hectare, of the alley crooping system, was determined.

Total content of carbon stored in biomass

The fractions of C in the tree biomass (above- and below-ground), litter and corn residues were determined using the dry combustion method (Kalra and Maynard 1991). This process involves the drying and weighing of samples, duplicated sample combustion in a kiln at 500 °C for 48 h, and finally, C determination. Total C content was determined by multiplying the dry weight of each individual component by the proportion of C contained in the total biomass of each component.

Soil organic carbon

To determine the fraction of carbon in the soil, soil organic matter was first determined using the dry combustion method (Ben-Dor and Banin 1989). The 1.72 factor proposed by Díaz-Romeu and Hunter (1982) was used for the conversion of OM to a carbon fraction. The storage of soil organic carbon (SOC) at a depth of 30 cm in both treatments was calculated using the laboratory results (bulk density and % of organic C in the soil) and the sample depth, summing the SOC at each depth interval. The SOC at each depth range was obtained using Eq. 2.

$$SOC = (CC * BD * SD)/20{,}000$$

Where SOC soil organic carbon (Mg C ha^{-1}), CC carbon content (%), BD Bulk density (t m^{-3}), SD sample depth (cm), and 20,000 m^{2} for the useful area of plot).

Total carbon storage

The total C storage in each tree species and litter was obtained by the sum of the total content of C. It is necessary that both be expressed in common units. To quantify the flows and reservoirs in an integrated manner, the system age was used to calculate the rate of accumulation, so that it could be added to the annual flow.

Statistical analysis

The biomass production data and the above- and below-ground C content of different tree species were analysed by a comparison of means using the Student t test. Where statistically significant differences were found, a Tukey test (95 %) was applied. The analyses was performed using Sigmaplot for Windows Version 11.0 (2008 Systat Software, Inc. San Jose, CA, USA).

Results

Tree biomass and C content

The a logarithmic model were fitted to the DBH data, providing determination coefficients (R^2) of 0.96; 0.95; 0.93 and 0.95, respectively (Table 2). These values can be explained based on the large volume of data (n = 160) obtained from the system with trees of the same age and the same experimental conditions.

On average, G.sepium and A. mangium stored a total of 33.75 kg of DM ha^{-1}, of which 19.01 Kg was within the stem, 8.40 kg was in the branches, 4.05 kg was in the coarse roots, and 2.1 kg was in the leaves. (Fig. 2a), which translates into a mean of 49.02 Mg C ha^{-1}. Trees with a DBH > 15 cm stored 25,6 kg DM/tree, more than that stored in trees with a DBH range of greater than 5 cm but less than 15 cm (16 kg DM/tree) and two times more than that stored in trees with a DBH<5 cm (12 kg DM/tree). Although the *L. leucocephala* trees with a DBH>15 cm provide the greatest quantity of DM, they represented only 12 % of the total number of trees in the system (Fig. 2b).

Fig. 2 Biomass production by tree component and total biomass (a), biomass per tree for each diametric class (b)

A storage of 226.00 Mg DM ha^{-1} was calculated for the tree total biomass of the system, which translates into a mean of 168.98 Mg C ha^{-1}. On average, each tree stored 22 kg C, of which 12.9 kg was found in the stem, 5.4 kg was in the branches, 2.7 kg was in the coarse roots and 1.4 kg was in the leaves (Table 3). Furthermore, it was determined that the C content was greatest in the trees with a DBH > 15 cm, presenting 16.34 kg C (Fig 2b)

Accumulation of litter and carbon content

The production of litter from the *A. mangium*, *G. sepium*, *L. leucocephala* and *C. fairchildiana* trees in the system was 79.3, 53.3, 45.8 and 31.5 Mg DM ha^{-1} $year^{-1}$, respectively. From June to December, the litter accumulation was less than during the remainder of the year. The highest accumulation occurred during February (Fig. 3a). The litter accumulated an average of 7.73 Mg C ha^{-1} $year^{-1}$, with the largest amount accumulated at the *A. mangium* (9.3), followed by *C. fairchildiana* (7.5), *L. leucocephala* (7.3) and *G. sepium* (6.8) Mg C ha^{-1} $year^{-1}$ (Fig. 3b).

Fig. 3 Pattern of monthly accumulation of litter over 1 year in alley cropping system (a) Pattern of monthly accumulation of carbon in litter over 1 year in alley cropping system (b)

Soil carbon content

Differences in soil carbon content were observed between plots with tree species and control plots. The highest soil C content was found in depth of 0–10 cm, followed by 10–20 and 20–30 cm (Table 4). In the all treatments, the amount of C in the soil tended to decrease with depth; the highest amount was found at 0–10 cm, followed by 10–20 and 20–30 cm (Table 4).

Organic carbon stored in the soil

The greatest quantity of SOC was stored at a depth of 0–10 cm, followed by 10–20 and 20–30 cm. Significant difference were found between the amount of C stored in the treatments with species trees and the control (without trees) (Table 5).

Table 6 presents the balance of total C stored in the reservoirs (tree and soil biomass) as well as the mean flow (litter) of each of the evaluated treatment. The reservoirs stored the same quantity of C, presenting similar annual accumulation rates, differing only from the control. In the system, the soil and tree biomass stored 26.5 and 73.4 % of the total C, respectively. The flow of C in the L+A were greater than those in the other treatments. Upon calculating the annual total balance of C captured by the system (accumulation rate and annual flow), the L+A and G+A presented a slight advantage over the other treatments at 0.3 Mg C year^{-1}, representing a difference of 2.4 %.

Discussion

Tree biomass and C content

The accumulation of total biomass varied between the tree species of the system, however, agroforestry systems are highly variable, as can be expected, these values are a direct manifestation of the ecological production potential of the system, depending on a number of factors including site characteristics, land-use types, species involved, stand age, and management practices (Nair et al. 2009).

The tree component contributed on average with 56.5 Mg MS ha^{-1} to the total biomass in alley cropping system. The specie *A. mangium* and *G. sepium* contributed 59 and 67 Mg DM ha^{-1} to the total biomass in system, where the highest amount of biomass was due to the greater amount of stems. This additional contribution of woody biomass to the total biomass provides an advantage in the storage of more carbon.

In average, fifty-eight percent of the tree total dry weight was provided by the stems, 24 % by the branches, 12 % by the coarse roots, and only 6 % by the leaves (Fig. 3). The finding that the branches and roots presented the highest proportion of the dry weight could be due the diametric growth of the trees, which is enhanced by pruning every year.

A. mangium in particular, 60% of the total weight of the tree was supplied by the stem, 23% by the branches, 12% by the coarse roots and 6% by the leaves. *G. sepium* presented 59% for the stem, 24% for the branches, 11% for the coarse roots and 6% for the leaves. *L. leucocephala* presented 53% for the stem, 24% for the branches, 18% for the coarse roots and 6% for the leaves. *C. fairchildiana* presented 57% for the stem, 26% for the branches, 8% for coarse roots and leaves.

Villanueva-López et al. (2015) published similar results for the species *G. sepium*, presenting Fifty-four percent of the total dry weight tree was provided by the stems and 22% by the branches. The finding that the stems presented the highest proportion of the dry weight could be due to both the density of *G. sepium* and *A. mangium* wood, which was 0.81 and 0.84 g/cm^3 in the present study, and the diametric growth of the trees, which is enhanced by pruning every year.

Although some trees of *A. mangium* with a DBH > 15 cm produced large amounts of biomass, they are not common, representing only 11.6 % of the total trees present in the alley crooping system (Fig. 4) due to the age of 5 years system. However, This also represents an advantage in terms of C storage, as younger trees have a greater potential to store C in their biomass (Peichl et al. 2006).

The *A. manium* stored 35.8 Mg C ha^{-1} (Table 3) in the biomass tree total. According to Palma (2014), the carbon density in *A. mangium* increases at an early age, however, the increases show a declining rate as the tree approaches maturity which conforms to the findings of Heriansyah et al. (2007) and Peichl and Arain (2006). A benefit of this species is that 87 % of the C is stored in the stems, branches and coarse roots, components that remain in the system for a prolonged period of time (i.e., are reservoirs) and are not distributed in the system.

The highest contents of C were in *A. mangium* and *G. sepium*, mainly in the trunks. Although the other species have a greater amount of C in their components, carbon sequestration ends when the tree is pruned or dies. an advantage of the system of this region is that only thin branches and leaves are used as cover of the soil, the trunk remains in the systems for many years, whereas in other agroforestry systems the trunk is used as firewood, thus, most of the biomass of C rapidly returns to the atmosphere as CO_2.

Accumulation of litter and carbon content

The accumulation of litter in the system in alleys of this region is high, since every year the biomass of leaves and fine branches are deposited manually on the ground. however, the amount of carbon accumulated is not always related to the annual biomass production that is deposited under the soil. C/N ratio, decomposition rate and precipitation interfere with litter accumulation during the year. *A. mangium* was the species that maintained the largest amount of litter in the system during the year, about 6.6 Mg of litter per month. one of the factors that provides a lower accumulation and retention of litter in the system from June to December is the water restriction (Figure 1). In the month of February, the greatest accumulation occurs due to the pruning that is carried out annually and also at the beginning of the rainy season. The strong rains also provide a rapid decomposition of the litter, mainly for the species *L. leucocephala*.

Litter accumulation and carbon storage capacity were similar among the evaluated species (fig. 3a and 3b). The *A. mangium* was the species that had the largest accumulation of litter and stored the largest amount of carbon. this can be attributed to the crown size (larger branches), the high density of leaf cover, as well as the design and spatial extension of the trees within the system. In some cases, the growth rate of a species can be favored due to its habit of perpendicular growth, as is the case of *A. mangium*.

Furthermore, our results suggest that the system not only help to improve the physicochemical characteristics of the soil (Table 1) but also contribute modest amounts of C through the recycling of nutrients, making it an environmentally and economically sustainable system (Nyakatawa et al. 2011).

Organic carbon stored in the soil

The amounts of C stored in the soil in all treatments (1.8 Mg C ha^{-1}) (Table 4) were similar to those reported by Makumba et al. (2007), Oliveira et al. (2018) after 12 years of management, in the integrated crop-livestock-forestry systems and Aguiar et al. (2010). This similarity between systems is associated with the soil bulk density (BD), which average was 1.3, similar to the 1.4 (g/cm^3) reported by Aguiar et al. (2010) in an alley cropping system.

The amount of organic C recycled varied from 0.9 to 2.1 Mg C ha^{-1} in alley cropping system. After 5 years of continuous application of tree pruning, C was sequestered in the soil (0–30 cm) in treatment with trees was 1.2 times more than in soil control. We concluded that alley cropping system could sequester more C in the soil than soil uncovered. Looking at this contribution, it becomes clear that alley cropping system alone cannot solve the current climatic problems, but can only be one among a range of strategies. However, the implementation of agroforestry projects could be justified for many other reasons. First, increasing soil C greatly benefits agricultural productivity and sustainability. Second, given the improbability of obtaining any single mitigating method, adding modest contributions together appears to be a more realistic way of achieving CO2 reduction targets (Paustian et al. 1997).

In both systems, the highest amounts of C were stored in the 0–10 cm soil depth. These patterns could be associated with the physiochemical properties of the soil and of the amount of litter from trees (i.e., leaves, branches and twigs) that enters the system and the accumulation of OM from the growth and decomposition of the finest tree and roots. (Eldridge and Wong 2005; Kaonga and Bayliss-Smith 2009).

In addition, below ground, the tree roots penetrate into deeper soil layers than monoculture maize roots and bring nutrients to the surface via leaf fall, providing a better nutrient balance in the soil compared to monoculture maize systems. In the system, the higher concentration of OM in the first 10 cm of soil is probably the result in more rapid decomposition of the mulch by microorganisms, incorporating a greater quantity of OM into the surface layer. Additionally, leaf litter acts as mulch and reduces evaporation, surface runoff and erosion, hence protecting the topsoil, which contains more soil organic carbon and other soil nutrients than other soil layers (Villanueva-López et al. 2015).

The balance of C in each evaluated system was on average 97 % in the trees (above- and below-ground), litter and corn residues (Table 6). These results are optimistic. However, increasing stocks of C in a given period of time is just one step, the fate of these stocks is what determines the carbon sequestration. In alley cropping system C sequestration is a dynamic process and can be divided into phases. At establishment, C and N loss of native vegetation and soil probably occurs. Then follow a quick accumulation phase and a maturation period when tons of C are stored in the boles, stems, roots of trees and in the soil. At the end of the accumulation period, when the aerial biomass is harvested and deposited in the soil, part of the C will be released back into the atmosphere. Therefore, effective sequestration can only be considered if there is a positive net balance of an initial stock after some years. These characteristics illustrate the difficulty of the system, of the Amazon frontier region, in storing organ carbon in the soil. however, this system compared to the traditional cultivation system used in this region has greater potential to store C.

Conclusion

The results of this study demonstrate that the presence of *A. mangium* trees in the alley cropping system contributed 31 % of total stored carbon. The flows of C in both of the evaluated systems were similar, except for the *A. mangium*. The litter production of the *A. mangium* species increased the annual flow of C by approximately 13%. Research into physical fractionation and the determination of non-complexed organic matter are necessary for a better understanding of the effects of the alley cropping system in soil C accumulation. Research at soil depths greater than 30 cm is necessary to acquire a better understanding of the effects of cattle-farming systems on C accumulation in the soil.

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Table 1 Mean values of the general characteristics of the alley cropping system evaluated in the Chapadinha, Maranhão, Brazil.

Characteristics	*L. leucocephala*	*G. sepium*	*C. fairchildiana*	*A. mangium*
Number of trees	300	320	270	320
System age (years)	5	5	5	5
Age of trees (years) Establishment time (months)	9-17	9-15	9-17	9-24
Average annual leaves biomass production (Mg ha^{-1})	4.00	7.00	4.00	5.00
Production aims	corn	corn	corn	corn
Altitude m.a.m.s.l	93	93	93	93
Land topography	flat	flat	flat	flat
Tree pruning	Annually	Annually	Annually	Annually
Technification level	Low	Low	Low	Low
Technical assistance	High	High	High	High
Number of dead trees	20.00	1.00	50.00	3.00
Soil pH	5.03	4.03	5.04	4.6
Soil bulk density (g dm^{-3})	1.23	1.21	1.34	1.42
Soil organic matter (g dm^{-3})	34.53	34.56	36.02	37.05
Soil nitrogen (%)	0.21	0.18	0.22	0.16

Table 2. Equations adjusted for above- and below-ground

Tree species	Equações	NSE$^{(1)}$	QMRes$^{(2)}$	R$^{2\ (3)}$
L. leucocephala	Tree biomass = EXP (3.53003 + 0.9254 * DBH - 0.07892 * DBH^2 + 0.0004784 * DBH^3)	0.90	3.1964	0.96
G. sepium	Tree biomass = EXP (3.12039 + 0.8244 * DBH - 0.08791 * DBH^2 + 0.0004198 * DBH^3)	0.89	3.1052	0.95
C. fairchildiana	Tree biomass = EXP (3.5270 + 0.9137 * DBH - 0.05783 * DBH^2 + 0.0003972 * DBH^3)	0.91	4.4121	0.93
A. mangium	Tree biomass = EXP (4.53203 + 0.9478 * DBH - 0.09812 * DBH^2 + 0.0005144 * DBH^3)	0.92	4.2244	0.95

$^{(1)}$Nash-Sutcliffe model efficiency coefficient; $^{(2)}$ Mean square of residue; $^{(3)}$ Coefficient of determination

Table 4 Influence of the sampling depth on storage of soil carbon content (Mg C ha^{-1}) in alley cropping system in Chapadinha, Maranhão, Brazil.

Soil depth	Plots with tree species	Plots without tree species (control)
0-10 cm	2.4a	1.6b
10-20 cm	1.4a	0.6b
20-30 cm	1.0a	0.5b
All depth (0-30 cm)	1.3a	0.6b

Different letters within each row indicate significant differences according to Tukey's test (p<0.05)

Table 4 Influence of the sampling depth on storage of soil carbon content (Mg C ha^{-1}) in alley cropping system in Chapadinha, Maranhão, Brazil.

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0-10 cm	2.4a	1.6b
10-20 cm	1.4a	0.6b
20-30 cm	1.0a	0.5b
All depth (0-30 cm)	1.3a	0.6b

Different letters within each row indicate significant differences according to Tukey's test (p<0.05)

Table 5 Influence of the sampling depth on storage of soil organic carbon (Mg C ha^{-1}) in alley cropping systems in Chapadinha, Maranhão, Brazil.

Soil depth	Plots with tree species	Plots without tree species (control)
0-10 cm	1.6a	1.1b
10-20 cm	0.5a	0.2b
20-30 cm	0.1a	0.1a
All depth (0-30 cm)	2.1a	0.9b

Different letters within each row indicate significant differences according to Tukey's test ($p<0.05$)

Table 6 Estimate of total carbon (Mg C ha^{-1}) balance in alley cropping systems in Chapadinha, Maranhão, Brazil.

Reservoirs	*L. leucocephala*	*G. sepium*	*A. mangium*	*C. fairchildiana*	Control
Tree biomass	39.04	45.20	53.06	31.68	-
Soil	1.4	1.4	1.4	1.4	0.7
Total C in system Reservoir	40.44	46.6	54.46	33.08	0.7
Accumulation rate (Mg C ha^{-1} $year^{-1}$)	8.09	9.32	10.89	6.62	0.14b
Flow	*L. leucocephala*	*G. sepium*	*A. mangium*	*C. fairchildiana*	Control
Litter	7.3	6.8	9.3	7.5	-
Corn Residue	0.25	0.22	0.31	0.12	0.22
System total C flow	7.55	7.02	9.61	7.62	0.22
Annual carbon captured by system	15.74	16.34	20.5	14.24	0.36

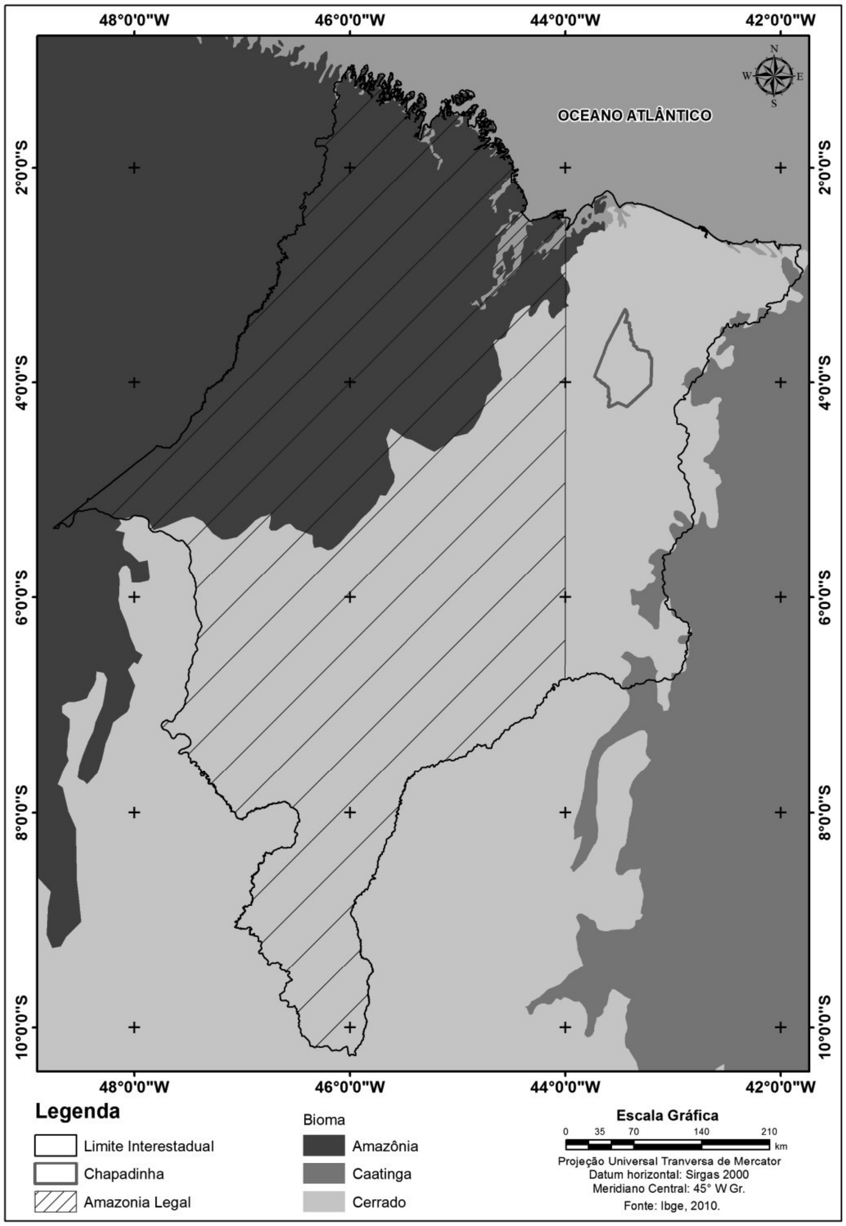

Figure 1 Distribution of precipitation, maximum and minimum temperature of Chapadinha, Maranhão, Brazil.

Decomposition and Nutrient Release of Tree Legumes in an Agroforest System

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Abstract

The research compared biomass production and nutrient release in an alley cropping system in two collection methods, the litterbag method and the direct collection method (Morley, Bennett, & Clark, 1964). The system was implemented in 2015, 2016 and 2017, at the Maranhão Federal University, Brazil, Maranhão. The experiment was a randomized block design with four treatments, consisting of leucaena+sombreiro (*Leucaena leucocephala* and *Clitoria fairchildiana*), leucena + acacia (*Leucaena leucocephala* and *Acacia mangium*), gliricidia + sombreiro (*Gliricidia sepium* and *Clitoria fairchildiana*) and gliricidia + acacia (*Gliricidia sepium* and *Acacia mangium*). In order to determine the remaining dry matter, nutrient release (N, P, K, Ca, Mg and Mn), the decomposition constants and the half-lives times of plant residues, 100 g of fresh material were conditioned in litterbags (50 g of each species), arranged on the soil surface. The second method was done by randomly throwing a collector on each plot in the same dimensions of the litterbags (0.40 x 0.40 m) and collecting the litter. For the two methods samples were collected at 0, 30, 60, 90 and 120 days after the start of the experiment. The C/N ratio obtained by the litterbags method underestimated the actual values up to the 30 days of collection, however, after 60 days in the field, these values were overestimated in comparison to the direct collection method in the litter. The litterbags method overestimated the release time (t1/2) for all nutrients studied.

Keywords: nutrient cycling; litter; system alleys, humid tropics.

1. Introduction

The litterbags method is the most used to determine the rates of decomposition of biomass applied in an agroforestry system, which allows experimental decomposition tests under field conditions. In this method, a known amount of tree biomass is placed in bags with suitable mesh sizes and then deposited on the soil surface. A large number of litterbags are installed at the beginning of the experiment, and collected periodically over time. The decomposition rates are determined from the mass loss placed on the litterbag. It consists of a simple and inexpensive method, widely used in bioassays (Hobbie & Gough, 2004).

In addition to this, a great advantage of the method is that the estimation of the decomposition rate from litterbags is based on the fact that the remaining material, besides providing data to make the "decomposition curves", also allows the analysis of the release of nutrients over time. However, this method has some limitations. The size of the mesh can exclude important decomposing organisms. In contrast, litterbags with mesh containing large holes can promote large losses of the contents, besides allowing the entrance of materials that were not considered in the installation of the experiment (Andrade, Caballero & Faria, 1999), such as leaflets, weeds or small particles of ground. Another technical and methodological impasse related to the use of litterbags consists in the quantification of the decomposition constant (k), which only takes into account the leaf fraction and fine branches to the detriment of the other fractions that compose the vegetal biomass deposited in the soil.

Another limitation derives from the failure to consider the destination of the lost litter, as well as not counting the interaction potential between the different components of the litter over time, with overestimation or underestimation of the nutrient contents released by the litterbags. Thus, it is clear that there are possible systematic differences between the two methods due to differences in the exposure of the sample surface and/or contact with the existing litter. Since few researches have compared the two methods simultaneously to determine the release of nutrients, the objective of this work was to compare the release of nutrients between litterbags method with a method of direct collection of litter in an alley crop system.

2. Material Studied

The experiment was developed in the years of 2015 to 2017. The local relief characterizes as a region of low plateau with vegetation of fields and enclosed covering flat relief. The experimental area was previously occupied by native secondary vegetation. The region of the study area is under humid tropical climate, has an average temperature of 29 ° C, maximum of 37 ° C and altitude of 110 meters above sea level. The rainy season is diverse between November and May.

The tree legumes were sown in January 2012, in rows spaced 2.0 m between rows and 0.5 m between plants. Two tree species with high quality of residues were used: leucena and gliricidia (*Leucaena leucocephala* and *Gliricidia sepium*), and two low quality tree species: shade and acacia (*Clitoria fairchildiana* and *Acacia mangium*), combined in rows so that each plot received the two residues simultaneously. The soil of the area was classified as Distortic Quartzite. Based on pre-planting soil analysis (Table 1), the entire experimental area was fertilized with 80 kg ha^{-1} of P_2O_5 as single superphosphate. The first nitrogen fertilization was 137 kg ha^{-1}, and the second was 89 kg ha^{-1} N in the form of urea.

The evaluation of the decomposition of the vegetal residues was initiated after the cut of the aerial part of the plants, in the year of 2016. Soon after the cut, samples were taken for the determination of the dry and fresh biomass and the levels of N, P, K, Ca in G. The first method of evaluating the nutrient release of plant residues was carried out by packing 100 g of fresh material (legume combinations) into bags made with plastic mesh (litterbags) with a mesh opening of 4 mm. The second method to evaluate the nutrient release of plant residues was carried out using a collector commonly used to estimate dry matter production in pastures (Morley, Bennett, & Clark, 1964), a jig - a detachable accessory, made of wood in the same dimensions of litterbags (0.40 x 0.40 m).The litterbags were arranged on the soil surface and the decomposition and nutrient release rates were monitored through collections at 0, 30, 60, 90 and 120 days after field installation. The template was thrown three times in each experimental plot and the litter was collected at 0, 30, 60, 90, and 120. At each collection date, the remaining litterbags and the template litter were taken to the laboratory and removed the soil particles. After this step, the samples were packed in paper bags and taken to the forced air ventilation oven at 65ºC until the material reached a constant mass for dry mass determination.

The dried material was processed in a Willey type mill (20 mm sieve aperture). N analysis was then performed according to the method recommended by Bremner and Mulvaney (1982). P and K were determined from nitric-perchloric digestion (Bataglia, Furlani, Teixeira, Furlani, & Gallo, 1983). The determination of P was made by colorimetry through the formation of the blue color of the phosphate - molybdate complex in the presence of ascorbic acid, and K by atomic absorption spectrophotometry (Brazilian Agricultural Research Corporation [EMBRAPA] 1997). The Ca, Mg and Mn determinations were made by atomic absorption spectrophotometry (Bataglia et al., 1983). The decomposition of residues and nutrient release followed the simple exponential model used by Rezende et al. (1999):

$$X = X_0\, e - kt \qquad (1)$$

Where: X = Dry matter amount remaining after a t period of time; Xo = Initial dry matter amount; k = decomposition constant; t = time, in days.

By rearranging the terms of this equation, it is possible to calculate the decomposition constant or value k:

$$k = \ln\left(\frac{X}{X_0}\right)/t) \qquad (2)$$

The half-life time is another important parameter in the evaluation of the decomposition of plant residues, expressing the period of time, in days, necessary for half of the material to decompose, or for half of the nutrients contained in the residues to be released. According to Rezende et al. (1999), it is possible to calculate the half-life time through the equation:

$$\frac{t1}{2} = \ln(2)\,/k \qquad (3)$$

The data were submitted to normality tests (Cramer Von-Mises) and homoscedasticity test (Levene), and, assuming these assumptions, were submitted to analysis of variance and the means compared by the Tuckey test ($p > 0.05$) with the InfoStat software (2014).

3. Results

The mean values of the initial nutrient contents are shown in Table 1. The litterbags presented high levels of N and Ca, the combination of G + A presented the highest N content (45.3 g kg^{-1}) in relation to the other combinations, and the combination of L + S presented the highest levels of Ca (10.78 g kg^{-1}) and Mg (7.71 g kg^{-1}) (Table 1). In initial litter contents the combination of G + A and L + A presented higher amount of N and C (Table 1).

TABLE 1: Initial levels of nutrients contained in the biomass obtained by the methods of litterbags and collecting litter in combinations of different legumes in a system in alleys.

Combined species in	N	C	P	K	Ca	Mg	Mn

Litterbags				g kg^{-1}			mg kg^{-1}
Leucena+sombreiro	35.3b	227.7	1.88^{a}	5.76a	10.78a	4.71^{a}	0.87c
Leucena+acacia	34.9b	553.8	1.76^{a}	9.93b	5.70b	1.84b	1.03b
Gliricidia+sombreiro	35.3b	322.4	0.53b	8.44b	6.02b	2.11b	1.24a
Gliricidia+acacia	45.3a	392.4	0.64b	4.99a	5.95b	1.51b	0.83c
Combined species in litter	N	C	P	K	Ca	Mg	Mn
				g kg^{-1}			mg kg^{-1}
Leucena+sombreiro	3.7b	503.2	0.62a	1.2b	3.9a	0.4 a	0.9b
Leucena+acacia	4.5a	657.0	0.26c	2.1a	1.4c	0.3 a	0.7c
Gliricidia+sombreiro	3.6b	518.4	0.70a	2.3a	2.1b	0.2 a	0.8b
Gliricidia+acacia	4.7a	855.4	0.37b	1.3b	1.2c	0.3 a	1.2a

Values represent averages of 8 repetitions; averages followed by equal letters in the columns do not differ by Tukey's test ($p > 0.05$).

The C / N ratio in the first and second collection (0 and 30) was higher for the litter. In the third collection (60 days) the C / N ratio was higher for litterbags, remaining larger until the last collection at 120 days (Table 2).

TABLE 2: C / N ratio of tree biomass combinations of different legumes and litter formed in a system in alleys, for 120 days.

Combined species in litter	0	30	60	90	120
Leucena+sombreiro	37.0 b	22.3b	11.0a	7.8a	6,8a
Leucena+acacia	32.5 c	27.5 a	9.5a	5.3b	5,0b
Gliricidia+sombreiro	39.1 a	21.2b	8.0b	5.0b	6,8a
Gliricidia+acacia	39.4 a	17.0c	7.5b	6.6a	6,3a
Combined species in litterbags	0	30	60	90	120
Leucena+sombreiro	6.4c	8.9a	24.5a	41.8b	82.6b
Leucena+acacia	15.8a	9.3a	24.3a	23.2c	84.9b
Gliricidia+sombreiro	9.1b	8.7a	24.5a	54.8a	107.6a
Gliricidia+acacia	8.6b	8.2a	23.9a	39.8b	77.6b

Values represent averages of 8 repetitions; averages followed by equal letters in the columns do not differ by Tukey's test ($p > 0.05$).

The Gliricidia+sombreiro and Gliricidia+acacia combinations were statistically more rapidly decomposed than the combinations of Leucena+sombrero and Leucena+acacia (Table 3).

TABLE 3: Parameters the equation $X = X0\ e^{-kt}$ adjusted the values of dry matter and dry of half-life time in year 2014, Chapadinha - MA.

Combined species	Decomposition Equation Parameters		
	k(days^{-1})	$t_{1/2}$ (days)	r^2
Leucena+sombreiro	0.005c	152a	0.94
Leucena+acacia	0.007c	120b	0.98
Gliricidia+sombreiro	0.017a	40d	0.97
Gliricidia+acacia	0.012b	61c	0.98

$t_{1/2}$ = half-life time.

In relation to the half-life and nutrient release, with the exception of nitrogen and phosphorus, all other litter nutrients had a shorter release time compared to litterbag residues (Table 4 and 5).

TABLE 4: Parameters of the equation $X = X_0 e^{-kt}$ adjusted the values of N, P, K, Ca and Mg and half-life time of four combinations of different legumes.

Combined species	Nutrient	k ($days^{-1}$)	$t_{½}$ (days)	r^2
Leucena+sombreiro	N	0.024	31	0.99
Leucena+acacia	N	0.023	30	0.98
Gliricidia+sombreiro	N	0.020	27	0.98
Gliricidia+acacia	N	0.029	24	0.95
Leucena+sombreiro	P	0.019	43	0.84
Leucena+acacia	P	0.015	63	0.95
Gliricidia+sombreiro	P	0.062	15	0.91
Gliricidia+acacia	P	0.016	49	0.54
Leucena+sombreiro	K	0.016	43	0.57
Leucena+acacia	K	0.02	42	0.95
Gliricidia+sombreiro	K	0.07	12	0.87
Gliricidia+acacia	K	0.014	49	ND
Leucena+sombreiro	Ca	0.024	30	0.90
Leucena+acacia	Ca	0.015	49	0.65
Gliricidia+sombreiro	Ca	0.016	68	0.98
Gliricidia+acacia	Ca	0.013	65	0.64
Leucena+sombreiro	Mg	0.01	63	0.93
Leucena+acacia	Mg	0.01	67	0.85
Gliricidia+sombreiro	Mg	0.003	66	ND
Gliricidia+acacia	Mg	0.004	54	ND
Leucena+sombreiro	Mn	0.006	75	0.72
Leucena+acacia	Mn	0.001	85	0.76
Gliricidia+sombreiro	Mn	0.02	35	0.78
Gliricidia+acacia	Mn	0.03	41	0.77

t ½ = half-life time. ^{2}ND = data not fitted to the simple exponential model according to regression analysis ($p < 0.05$).

TABLE 5: Parameters of the equation $X = X_0 e^{-kt}$ adjusted the values of N, P, K, Ca and Mg and half-life time of litter consists of four combinations of different leguminous trees, Chapadinha - MA, 2014.

Combined species	Nutrient	k ($days^{-1}$)	$t_{½}$ (days)	r^2
Leucena+sombreiro	N	0.003	112	0.72
Leucena+acacia	N	0.004	73	0.59
Gliricidia+sombreiro	N	0.009	84	0.55
Gliricidia+acacia	N	0.004	48	0.50
Leucena+sombreiro	P	0.010	64	0.73
Leucena+acacia	P	0.006	74	0.83
Gliricidia+sombreiro	P	0.010	40	ND
Gliricidia+acacia	P	0.010	70	0.57
Leucena+sombreiro	K	0.020	27	0.63
Leucena+acacia	K	0.030	26	0.75
Gliricidia+sombreiro	K	0.030	25	0.94
Gliricidia+acacia	K	0.030	24	0.98

Leucena+sombreiro	Ca	0.020	38	0.70
Leucena+acacia	Ca	0.020	37	0.90
Gliricidia+sombreiro	Ca	0.010	36	0.93
Gliricidia+acacia	Ca	0.020	35	ND
Leucena+sombreiro	Mg	0.006	11	0.83
Leucena+acacia	Mg	0.007	13	0.62
Gliricidia+sombreiro	Mg	0.008	23	0.58
Gliricidia+acacia	Mg	0.008	25	ND
Leucena+sombreiro	Mn	0.001	71	0.68
Leucena+acacia	Mn	0.02	66	0.61
Gliricidia+sombreiro	Mn	0.03	53	0.72
Gliricidia+acacia	Mn	0.03	34	0.78

t ½ = half-life time. [2]ND = data not fitted to the simple exponential model according to regression analysis ($p < 0.05$).

4. Discussion

The nutrients present in the biomass of the litterbags at the beginning of the experiment present higher levels of nutrients when compared to the litter nutritional contents. This was due to the biomass of litter that was already in the process of decomposition for a year in the field, without the contribution of new tree biomass and the biomass present in litterbag was fresh biomass. In litterbags the combination of G + A showed the highest N content in relation to the other combinations, Moura, et al. (2009, 2012) and Schwendener (2005) also found similar values for N content in combinations that used gliricidia as biomass for ground cover.

Nitrogen is one of the main limiting factors of decomposition. It determines microbial activity and mineralization influences of organic C (Currie & Aber, 1997). The rate of mineralization of an organic substrate can usually be predicted by its C / N ratio or the N content. When the C / N ratio is less than 20 or the N content of more than 2.5%, N is mineralized and the decomposition of the residues is rapid. In contrast, N tends to be immobilized when the C / N ratio is greater than 20 and the decomposition of the residues is delayed (Currie & Aber, 1997).

This study shows that the C/N ratio of the two collection methods varied over the experimental period (120 days). Differences were observed in the C/N ratio between residues that were in litterbags and residues collected directly in the litter (Table 2). At day 0 the differences found between the two methods of collection were already expected, since the litter was in the process of decomposition for a year without addition of biomass. However, after 30 days, the C / N ratio remained low for the residues analyzed in the litterbags, which did not correspond to the values for the litter. After 60 days, the opposite effect was observed, where the C / N ratio decreases to the litter and begins to increase to the residuals in the litterbags. This behavior was observed up to 120 days.

It should be noted that the nutritional requirements of a crop intercropped with tree legumes through biomass input do not depend exclusively on the quantity and content of the nutrients contained in the material, but mainly on the transfer efficiency of these nutrients (Ferraz Júnior, 2004), which is linked to the low C/N ratio. The data obtained in this experiment leads to the conclusion that the mixture of the new biomass contribution with the existing litter modifies the C/N ratio, so the results for this relation obtained by the litterbags method are underestimating the real values up to 30 days and overestimating after 60 days in the field (Table 2).

Research has shown that there are a number of factors that influence the decomposition process, such as environmental factors, soil organisms, organic matter quality and soil management, which are also crucial in this process (Ferraz Júnior, 2004; Fortes, Balieiro & Franco, 2004).

the difference of decomposition between G + A, G + S and L + S, L + A may be due to the environment in which the material to be decomposed is located. Berg and Mc Claugherty (2008) suggested that greater moisture can cause a lack of oxygen for decomposers, for example white rot fungi, uses oxygen-dependent peroxidases. Even in an environment, not completely anaerobic, such as litterbags, the least amount of oxygen to litter can have clear effects. A general effect is slower decomposition. In addition, an incomplete metabolism may cause the formation of organic acids, for example, acetic acid, not only generating a lower pH but also having an antimicrobial effect (Berg & Mc Claugherty, 2008).

Another possible explanation for the greater decomposition of these treatments (L + S and L + A) may be the high carbon content (Table 1) in the litter of these treatments. The presence of C in litter may have induced the production of a greater variety of enzymes, which in turn may have increased the ability of microorganisms to decompose different types of substrates (Chapman, Newman, Hart, Schweitzer & Koch, 2013).

However, the L + A combination also presented high levels of C in the litter. In slower decomposition combinations, decomposers could be limited by the quality of the source of C (for example, lignin ratio), by the amount of N or by its interaction (Hoorens, Coomes & Rien, 2010).

The greatest difference between the half-life times (G + A = 61 days and L + S = 152 days) also showed significant differences in N contents (Table 1), both litterbags and litter. Similar results were found by Harguindeguy et al. (2008), where the fastest rate of decomposition was found in combinations with higher nitrogen content and greater heterogeneity in non-labile compounds.

In the combination of G + S, the resources may have been more easily degradable and available for decomposers, leading to an overall high availability of nutrients in the combination and allowing the transfer of nutrients to the low quality litter, thus enhancing decomposition. Other mechanisms, such as dilution of secondary compounds, improvement of microenvironmental conditions, or the effects of the specific compound, should not be discarded, however our experimental design does not allow us to draw conclusions along these lines.

In another aspect, this combination (G + S) was the one with the highest levels of C in the two collection methods. If the decomposers are limited by the amount of C present in rapidly decomposed species, then when a higher source of C, or a different source of C is added, decomposition can be accelerated (Hoorens et al., 2010; Berglund, Agren & Ekblad, 2013).

From the values k, the following order of release was established for the litterbags method: K> N> P> Ca> Mg, and for the method of collecting the litter the following order of release was established: P> Mg> N.

The longest half-life found for N was the combination of L + S, for the two collection methods, however the difference between them is great (112 days for litter residues and 31 days for litterbag residues). In this combination, which presented slow decomposition and slow release of N in the litter, the decomposers could be limited by the quality of the source of C (for example, lignin ratio), by the amount of total N or by their interaction (Hoorens et al., 2010).

Another possible explanation is that the N content in combinations with high initial lignin content suggests that antagonistic effects could be related to the formation of recalcitrant N-lignin complexes in these combinations (Berg & Mc Claugherty, 2008). The initial lignin content found for this combination is (214 Mg ha^{-1}) (Moura et al, 2009), almost double the ideal value, which is usually the consequence of this combination to retard decomposition and nutrient release (Rahman, Tsukamoto, Rahman Md, Yoneyama & Mostafa, 2013).

A difference of 25 days less P release was observed for the litterbag method. The same occurred for K, with a difference of 13 days less for the litterbag method as well (Table 4 and 5).

The Ca contents of the gliricidia treatments were released more slowly than the treatments with leucena, contrary situation observed in the K contents. However, when comparing the half-life times of the two types of collection it was observed that in litterbags the release of calcium was approximately 50% slower than in the litter (Table 4 and 5). A possible explanation for this difference is that in the litterbags there was a higher concentration of fungal colonies compared to the litter environment, what was observed in the field is that litterbags even with a suitable mesh opening provide a higher moisture content compared to litter. This may have favored a longer period of Ca accumulation, which is due to the absorption of this element into fungal hyphae as documented by Cromack et al. (1978) and Swift et al. (1981).

Berg (2014) reported that groups of microorganisms that cause white rot and brown rot can be related to N and Mn contents. Fungi that cause white rot have the ability to completely degrade lignin and lignified tissues, whereas microorganisms that cause brown-colored rot are limited to breaking the side chain of the aromatic nucleus of the lignin molecule (HATAKKA, 2001). Our results, observed in the field, showed higher amounts of white rot in the combinations of gliricidia, whereas brown rot was observed in greater amounts in the combinations with leucena.

This result is compatible with the N and Mn contents found in this study. Combinations with gliricidia had higher levels of N and Mn. Berg (2014) reports that the litter in which white rot fungi dominates, degradation would remain unimpeded, especially at low N concentrations, which was also observed in our study, where combinations with gliricidia showed faster decomposition than combinations with leucene. According to Hatakka (2001) almost all fungi of white rot have Mn peroxide (MnP) and their activity would be related to the availability of Mn. In contrast, no brown rot fungus was found with MnP.

Observing the results of the N and Mn contents of this study, we can see that litter samples with a high concentration of Mn (G+A and G+S) may favor the invasion of white rot fungus instead of rot fungi brown. Thus, the higher the concentration of Mn, the better the support for the growth of fungi of white rot, which in turn would support a faster decomposition in the humid tropics.

5. Conclusions

The C/N ratio obtained by the litterbags method is underestimating the actual values up to 30 days of collection and overestimating after 60 days in the field. The litterbags method overestimated the release time ($t_{1/2}$) for all nutrients studied.

In particular, there is a need to differentiate how the decomposition environment (eg soil characteristics, soil fauna, temperature and precipitation) are influencing these effects inside and outside litterbags.

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Weed Communities in alley cropping system of periphery Amazonia: Comparison between Corn (Zea mays) BR473 and Corn (AG1053)

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ABSTRACT: The humid tropics of the Amazon frontier region, being recently transformed from cutting and burning agriculture in agroforestry systems, represents an interesting scenario to understand the early stages of weed community assembly and its relationship with crop identity and management. Our aim was to characterize the weed communities in corn (Zea mays L.) BE473 andAG1053. Weed surveys were carried out during four consecutive years in an agroforestry system, composed of three different tree species: *Leucaena Leucocephala*, *Gliricidia sepium* and *Acacia mangium*. Floristic composition was compared within and between crops, and the additive partition of dissimilarity based on abundance of Bray-Curtis was calculated.

We compared the frequency and mean cover of functional groups between crops through generalized linear models. Finally, canonical correspondence analysis was carried out to analyze the associations between floristic composition and agronomic variables. Mean alpha and gamma diversity was greater in corn BR473 (27.0 and 40 species, respectively) than in AG1053 (15.0 and 22 species, respectively). Furthermore, species composition of weed communities was lower where the soil cover was of *Acacia mangium* or *Gliricidia sepium*.

Introdução

Marginal lands the maranhense Amazon for agriculture are not only less productive, but they are also usually more susceptible to degradation due to continuous cutting and burning practices. On the other hand, in a new alley cropping system, the composition of weed species is set up in response to periodic and episodic agricultural interventions, such as deposition of soil residue, shading and fertilization. Therefore, in the system current species composition of weed communities is also influenced by both the floristic composition of the original vegetation and the introduction of new species.

Weed seedbank entangles the species compositions of past and current weed communities, which are in turn affected by recurrent farming practices, thus determining the future composition of weed communities and soil seedbank (Cardina et al. 2002).

In systems with alleles, the use of tree legumes is essential for the stability and success of the system, assuming that these trees improve soil fertility through biological nitrogen fixation and nutrient recycling. At the same time, tree species, especially the legume family, with allelopathic activity, can play a crucial role in the stability of agroforestry systems, mainly due to the possibility of controlling weed infestation (Souza Filho and Alves, 1998).

In this system, we can observe characteristics favorable to weed control, such as shading. According to MACCLEAN et al. (2003) reported three efficient strategies for weed control in favor of the weed control system: shading, which can reduce the density of shade-sensitive species, prevent the emergence of weed seeds as a function of deposited mulch to soil and improve soil fertility over time due to the decomposition of residues applied to the soil, which ultimately changes the composition of herbs and sharpen the competitive power of crops.

Furthermore, corn crop dominance over weeds is also a determining factor in weed community assembly. Crop dominance is defined as the structuring influence of dense and homogeneous stands of crop plants over the subordinated, companion weeds (Poggio and Ghersa 2011).

Characterizing and comparing the floristic and functional compositions of a weed community in a new alley cropping system, in an area recently transformed from cutting and burning agriculture are a valuable contribution to the study of ecological processes under weed community assembly. Here, our objective was to compare the weed communities of two varieties of maize cultivated under an alley cropping system. Initially, we characterized the taxonomic and functional compositions of groups of weed communities in each corn variety, and then we analyzed the associations between weed communities and the management used in the alley cropping system and productivity.

Materials and methods

Site description

The experiment was performed in an experimental field in Chapadinha, Maranhão, Brazil at 3° 44′ 30″ S and 43° 21′ 37″ W, which is located in the northeast of the country. The region has a hot and semi-humid equatorial climate with a mean precipitation of 2100 mm year^{-1} and two well-defined seasons, a rainy season that extends from January to June and a dry season with a water deficit from July to December (Fig 1). The soil in the experimental area is Arenic Hapludult.

Weed Surveys

All sample fulfilled the following requirements (Mueller-Dumbois and Ellen berg 1974): (1) survey area was large enough to contain all species belonging to the weed community (at least 25 to 100 m^2 for each plot the alley cropping system), (2) habitat conditions were uniform within each plot, and (3) crop cover was homogenously distributed. Field margins plots were excluded. The alley cropping systems were set out in a randomized complete block design with four replicates in a plot size of 10 m x 4 m.

The legumes used were *Gliricidia sepium, Acacia mangium* (A), *Leucaena leucocephala* (L) and control (without the use of tree legumes). Two systems were surveyed, one system with QPM maize (BR 473) and one with Hybrid corn (AG 1053) totaling 1,280 m^2 (32 qpm plots and 32 hybrid plots). Weeds in these fields were surveyed during a period of 2 week in March 2015, 2016 and 2017. This period corresponds to early and post flowering of corn. In each field, three trained persons recorded weed cover in a zigzag pattern. Weed cover was estimated for each weed species by the adapted Braun-Blanquet method (Muelle-Dumbois and Ellenberg 1974).

Functional Classification of Weed Species

Weed species were classified according to their leaf type (monocotyledonous, dicotyledonous), photosynthetic pathway (C3, C4), and life cycle (perennial, annual) as an indicator of resource use; status (native, nonnative) as an indicator of original vegetation legacy; dispersion strategy (anemochory, zoochory); and height (short, medium, tall). The grouping criteria for classifying plant height was in comparison with crops corn, as a reference (1.6- to 2.0-m high). The "short" category corresponds to plants shorter than 30 cm, always shaded; "medium" species are between 30 and 150 cm, slightly shaded, and almost at the same height as crops; "tall" species are taller than 160 cm. Finally, Légère and Samson (1999) determined that the classification scheme in annual/perennial, and monocotyledons/dicotyledons is particularly appropriate for describing herbicide selectivity patterns.

Data Analysis

The floristic structure of weed communities was analyzed through species diversity and composition, whereas functional structure was described by grouping species according to particular traits and common characteristics. Regional species richness (gamma diversity) was calculated for each corn (AG1053 and BR1053).

Gamma diversity is obtained by accumulating the total number of weed species, without repetition, that were registered in all plots. Mean species richness (field, local, or alpha diversity) was obtained by averaging the number of species found in each year of a given corn type. The frequency of species occurrence at a regional level (also denominated "constancy") and mean cover were calculated for each species.

Floristic composition was compared between corn crops by calculating the additive partition of the abundance-based Bray-Curtis dissimilarity (Baselga 2013).

Bray-Curtis dissimilarity ranges between 0 and 1, where 0 means that two systems have the same floristic composition (i.e., they share all weed species), whereas 1 means that two systems have totally different floristic compositions (i.e., they do not share any weed species). The abundance-based Bray-Curtis dissimilarity (dBC) was separated into two components (Baselga 2013). One of them, the balanced variation component of the Bray-Curtis dissimilarity (dBC-bal), represents the changes in species abundance between systems (i.e., the abundance of some species declines between two given systems in the same magnitude as the abundance of the other species increases between the same systems).

The other one, the abundance gradient component of the Bray-Curtis dissimilarity (dBC-grad), represents the decrease of weed abundance from one treatment to another. Values of both dBC-bal and dBC-grad were calculated with the function bray.part to compute the dissimilarities using the ‘betpart’ package (Baselga and Orme 2012). Abundance ased Bray-Curtis dissimilarity was then obtained by summing up both components (dBC=dBC-bal +dBC-grad). Calculations were performed in R v. 3.3.3 (R Development Core Team 2014).

To analyze functional groups of weeds with good performance in agroforestry systems, we compared the frequency and mean cover among functional groups between crops and for the whole data set. For analyzing the frequency of occurrence of weed species, we carried out a binomial generalized linear model, using the logit link function and compared by chi-square test. For mean cover analyses, we carried out a generalized linear mixed model, using Poisson distribution and log link function and compared by Fisher’s LSD. The analysis was performed with R v. 3.0.3 (R Development Core Team 2014).

Results and Discussion

Floristic Comparison

Forty-five weed species were recorded in the agroforestry system grown with corn BR143 and AG1053 crops surveyed in the pre-Amazon region. Twenty-six species had frequencies lower than 2%, which included 25 species that were found only at a single site. This high proportion of rare species, mostly native annuals, suggests a strong presence of the original vegetation in these recently cultivated systems (Table 1). Sixteen botanical families were represented in the 45 species that were taxonomically determined (2 rare species remained unidentified due to their nonreproductive phenological stage).

Poaceae (13 species) and Asteraceae (06 species) families comprised the largest numbers of species of monocotyledons and dicotyledons, respectively (Table 1). The weed community in the corn parcels qpm was more species rich than that of corn AG1053. Mean alpha diversity at field scale (species richness) was greater in corn BR1053 (27.0 species) than in AG1053 (15 species; Kruskal-Wallis, P=0.021). Total number of species surveyed in the study region (gamma diversity) was also greater in corn BR473 (40 species) than in corn AG1053 (22 species). Greater diversity in corn qpm was due to the presence of more rare species, which were mostly native (Tables 1 and 2).

Moreover, most species listed in BR473 corn had a greater frequency of occurrence at the regional level than in AG1053 corn (Figure 2). Similarity between plots AG 1051corn was higher (low dBC) than plots BR 473 corn or between of both crops (Figure 3), whereas species abundance was higher in maize qpm. In addition, distributions of dissimilarity measures for qpm corn or between fields of both corn were highly similar in terms of median, quantiles, and range values (Figure 3).

In alley cropping system, our findings indicate that weed communities are less variable in corn AG1053 crops (i.e., low beta diversity) than among qpm corn crops (i.e., high beta diversity). Our results provide further indication that contrasting corn varieties, such as QPM and Hybrid, can impose different filtering effects on companion weed communities, which will consequently result in the occurrence of a different number of species.

Corn plants showed differences in height and spike insertion. Differences in crop identity that differ starkly in their canopy and rhizosphere structures may create different microenvironmental heterogeneity above- and belowground (Gao et al. 2010; Gitelson et al. 2014), which potentially allows for the occurrence of some weed species adapted to the specific crop environment, while other species are filtered out (Booth and Swanton 2002; Swanton et al. 1993). QPM maize crowns rarely achieved complete ground cover, so radiation interception was rarely maximal under productive conditions. On the other hand, AG 1051 cups often reached full ground cover, which consequently restricted the proportion of sunlight reaching the ground, reducing the light available for weed development.

Functional Composition Was different between BR 473 and AG1053 Corn

The frequency of functional groups was quite different between both types corns (Table 2). The higher frequency of perennials, c3, and native species (Table 2) likely resulted from the relatively recent inception of alley cropping system in the region (seven years). Evidence indicates that annuals and dicotyledons decrease as time of continuous no-tillage management increases (Mas et al. 2010). In addition, medium-height species could have been favored by intermediate light interception conditions in comparison with the more shaded, short species and the rarer, and shorter native species (Anderson et al. 1970).

There are differences in the cover of species among functional groups of weed communities in the amazon maranhense region, where weed communities differed between corns (Table 3). There is evidence that crops limit weed abundance through competition, principally for light (Mhlanga et al. 2016), and although we have not demonstrated this, our results agree with this idea. Many of the rare species present, principally in qpm corn, are annual (probably due to the posterior successional stage of these agricultural soils) and are associated with no-tillage practices (de la Fuente et al. 1999).

Weed Community Structure Was Related to the tree species used as soil cover

Floristic and functional composition was also affected by the different tree species used as soil cover in the two types of maize (Table 3; Figures 2 and 3). The species *Leucaena leucocephala* was the one with the highest number of invasive species. The species *Gliricidia sepium* and *Acacia mangium* were the ones that presented smaller species of weeds in their plots. Our results are also in agreement with previous research (Santos et al.,2016), in which leguminous trees were used to have a significant effect on the species composition of weed communities.

Our results show that covering the soil using biomass of the *Acacia sepium* and *Gliricidia sepium* species can reduce weed abundance. In alley systems, this may be related to the fact that the organic material of the trees was integrated into the soil, resulting in an improvement of soil quality. Moreover, in the post-harvest period, tree shading could be a factor in weed suppression (Nestel & Altieri, 1992). Additionally, Midega, Pittchar, Salifu, Pickett, and Khan (2013) demonstrated that covering the soil with litter from plants significantly reduced emergence of weed plants. Improvement in soil nutrient availability has been known to contribute to weed control (Barrios, Kwesiga, Buresh, Sprent, & Coe 1998; Sileshi, Mafongoya, et al. 2008). This is partly because of the better growth that allows crops to out-compete weeds. The beneficial effects of the association of trees and crops may also be due to the moderation of microclimate by trees (Nestel & Altieri 1992; Sileshi, Mafongoya, et al. 2008; Barrios, Sileshi, Shepherd, & Sinclair 2012).

Our study suggests that the original vegetation of the Maranhão Amazon had high representatively in the floristic composition in weed communities due to the high proportion of annual, dicotyledonous and native species, which reflected the recent transformation of these agricultural lands into alley cropping system (de la Fuente et al., 1999, Froud-Williams 1986, Mas et al., 2010). Overall weed cover was very low in this alley cropping system, indicating that the high cover leguminous trees associated with no-tillage technologies were effective, possibly due to local relative absence of resistant biotypes in the original vegetation. Therefore, this system represents an opportunity for the design of integrated management strategies that could help reduce the use of chemicals and, consequently, the appearance of resistant variants.

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Table 1. Binomial and common names, family, dispersion strategy, life cycle, morphotype, origin, frequency, and mean cover for weeds species recorded in field surveys

Species	Common name	Family	Dispersion	Life cycle	Morph-otype	Origin	BR 473	AG 1053	BR 473	AG 1053
Alternanthera brasiliana (L.) Kuntze	Parrotleaf	Amaranthaceae	Anm	A	D	N	0.05	0.07	1.49	2.09
Alternanthera tenella Colla	flora of North America	Amaranthaceae	Anm	A	D	N	0.20	0.36	4.66	10.22
Amaranthus deflexus L	large-fruit amaranth	Amaranthaceae	Anm	A	D	NN	0.02	-	0.74	-
Abrus precatorius L	Jequirity	Fabaceae-Faboideae	Anm	A	D	N	0.02	0.036	14.15	1.04
Aeschynomene americana L	shyleaf	Fabaceae-Faboideae	Zoo	A	D	N	0.02	-	1.49	-
Brachiaria brizantha (hochst. Ex A.Rich.) Stapf	Common signal grass	Poaceae	Anm	A	M	N	0.02	-	0.74	-
Brachiaria mutica (Forssk.) Stapf	Mauritius grass	Poaceae	Anm	A	M	NN	0.02	-	0.74	-
Brachiaria subquadripara (Trin.) Hitche	Tanner grass	Poaceae	Anm	A	M	NN	0.02	-	2.98	-
Cenchrus echinatus L	southern sandbur	Poaceae	Anm	A	M	N	0.20	0.14	2.51	3.39
Cynodon dactylon (L.) Pers	Bermuda grass	Poaceae	Anm	A	M	NN	0.10	0.11	1.12	3.13
Centratherum punctatum Cass	Lark daisy	Asteraceae	Anm	P	D	N	0.02	-	2.23	-
Chicorium intybus L	French endive succory	Asteraceae	Anm	P	D	NN	0.02	-	2.23	-
Commelina benghalensis L	Benghal dayflower	Commelinaceae	Anm	P	M	N	0.02	-	1.49	-
Cyperus iria L	Rice flat sedge	Cyperaceae	Anm	A	M	N	0.15	0.43	1.61	4.17
Chamaesyce hirta (L.) Millsp	Asthma-plant	Euphorbiaceae	Anm	A	D	N	0.05	-	3.35	-
Digitaria bicornis (Lam.) Roem. & Schult	crabgrass	Poaceae	Anm	A	M	NN	0.05	0.14	2.61	5.74

Digitaria horizontalis Willd.	Jamaican crabgrass	Poaceae	Anm	A	M	NN	0.02	-	4.47	-
Digitaria sanguinalis (L.) Scop	hairy crabgrass	Poaceae	Anm	A	M	NN	0.02	-	0.74	-
Echinochloa colona (L.) Link	jungle rice	Poaceae	Anm	A	M	NN	-	0.04	-	-
Eleusine indica (L.) Gaertn	Indian goosegrass (C3)	Poaceae	Anm	A	M	NN	0.05	0.04	1.86	3.13
Eragrostis airoides Nees	lovegrass	Poaceae	Anm	A	M	N	0.05	0.14	1.12	5.74
Eragrostis ciliaris (L.) R. Br	lovegrass	Poaceae	Anm	A	M	NN	0.05	0.18	12.29	9.18
Eragrostis plana Nees	South African lovegrass	Poaceae	Anm	A	M	NN	-	0.03	-	-
Eclipta alba (L.) Hassk	American false daisy	Asteraceae	Anm	A	D	N	0.02	0.11	0.74	3.48
Emilia coccínea (Sims) G. Don	Tassel Flower	Asteraceae	Anm	A	D	N	0.05	0.11	1.12	1.74
Emilia fosbergii Nicolson	Florida tasselflower	Asteraceae	Anm	A	D	N	0.02	0.04	0.74	1.04
Fimbristylis autumnalis (L.) Roem. & Schult	Slender fimbry	Cyperaceae	Anm	A	M	N	-	0.07	-	-
Hyptis atrorubens Poit	Marubio oscuro	Laminaceae.	Anm	Pl	D	N	-	0.04	-	-
Hyptis suaveolens (L.) Poit	pignut	Laminaceae	Anm	P	D	N	0.02	-	1.49	-
Ipomoea fimbriosepala Choisy	chi and shu	Convolvulaceae	Anm	A/P	D	N	-	0.04	-	-
Ipomoea ramosíssima (Poir.) Choisy	Morning glory	Convolvulaceae	Anm	A/P	D	N	0.02	-	0.74	-
Kyllinga brevifolia Rottb	Shortleaf spikesedge	Cyperaceae	Anm	A/P	M	N	0.07	0.14	2.98	2.87
Mimosa setosa Benth	Mimosa	Fabaceae-Mimosoideae	Anm	A	D	N	0.07	-	0.50	-
Malvastrum coromandelianum (L.) Garcke	Three-lobed false mallow	Malvaceae	Anm	A	D	N	0.10	-	0.74	-
Mollugo verticillata L	green carpetweed	Molluginaceae	Anm	A	D	N	0.05	0.11	2.61	3.82
Praxelis pauciflora	Praxelis	Asteraceae	Anm	A	D	N	0.24	0.25	2.83	5.21

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paspalum paniculatum L	Arrocillo	Poaceae	Anm	A	M	N	0.02	-	0.74	-
Pycreus lanceolatus (Poir.) C.B. Clarke	EPIPHYTIC FLATSEDGE	Cyperaceae	Anm	A	M	N	0.05	0.11	3.35	10.78
Scoparia dulcis L	licorice weed	Plantaginaceae	Anm	A	D	N	0.07	-	0.74	-
Sida glaziovii K. Schum	Brazilian sida	Malvaceae	Anm	A	D	N	0.02	0.04	0.74	2.09
Sida urens L	TROPICAL FANPETALS	Malvaceae	Anm	A	D	N	0.02	0.04	0.74	1.04
Sporobolus indicus (L.) R.Br	Smut grass	Poaceae	Anm	A	M	N	0.12	0.2	3.87	5.74
Spermacoce latifolia Aubl	OVAL-LEAF FALSE BUTTONWEED	Rubiaceae	Anm	A	D	N	0.27	0.46	8.40	12.03
Senna uniflora (Mill.) H.S.	One Leaf Senna	Fabaceae-Caesalpinioideae	Anm	A	D	N	0.02	0.04	1.49	1.04
Irwin & Barneby	white buttercup	Turneraceae	Anm	A	D	N	0.02	0.74	0.14	1.30

Table 1. Binomial and common names. family. dispersion strategy. life cycle. morphotype. origin. frequency. and mean cover for weeds species recorded in alley cropping systems^{aa} *Abbreviations: D. dicotyledons; M. monocotyledons; N. native; NN. nonnative (exotics and cosmopolitans);* Anm. Anemochory; Zoo. Zoochory; A. annual; P. perennial.

Table 2. Binomial generalized linear model to compare the frequency of functional groups between the two maize varieties

Functional classification	Categories	Corn BR143	Corn AG1053	Parameters[b]
Morphotype	Dicotyledonous	25.27 a	27.10 a	Crop:NS
	Monocotyledonous	22.39 b	29.68 a	Morphotype: $\chi_2 = 158.5$, df = 1, $P < 0.0001$
Photosynthetic pathway	C3	23.93 b	33.51 a	Crop:NS
	C4	24.23 b	27.06 b	Photosynt: $\chi_2 = 4.57$, df = 1, $P = 0.03251$
Origin	Native	25.52 b	30.79 a	Crop:NS
	Nonnatives	13.63 c	19.76 c	Status: $\chi_2 = 176.6$, df = 1, $P < 0.0001$
Life cycle	Annuals	24.24 b	29.65 b	
	Perennials	11.10 c	47.78 a	Crop × cycle : $\chi_2 = 6.358$, df = 1, $P = 0.01169$
Dispersal strategy	Anemochory	23.35 b	28.34 a	
	Zoochory	7.20 c	-	Crop × dispersal : $\chi_2 = 4.8434$, df = 2, $P = 0.08877$
Plant height	Short	17.37 c	25.63 b	Crop:NS
	Medium	25.03 b	37.51 a	Height: $\chi_2 = 282.75$, df = 2, $P < 0.0001$
	Tall	29.57 b	26.38 b	

[a] *Different lowercase letters indicate significant differences within each functional classification group, according to chi-square test. b Abbreviation: NS, not significant; photosynt, photosynthetic pathway. *P < 0.1*

Table 3. Agronomic variables of corn BR473 and AG1053

Agronomic variables	BR473			AG1053		
	2015	2016	2017	2015	2016	2017
Grain yield (Mg ha^{-1})						
Leucaena leucocephala	2.9	2.8	2.7	3.7	3.9	4.5
Gliricidia sepium	4.7	4.6	4.7	4.5	4.6	4.8
Acacia mangium	4.7	5.0	5.4	4.1	4.2	4.7
Fertilization rates (kg ha $^{-1}$)						
Nitrogen (Kg ha^{-1})	60	60	60	60	60	60
Phosphorus (Kg ha^{-1})	80	80	80	80	80	80
Potassium (Kg ha^{-1})	40	40	40	40	40	40
Applied Legume Biomass (Mg ha^{-1})						
Leucaena leucocephala	2.5	2.9	4.1	2.5	2.9	4.1
Gliricidia sepium	10.3	12.7	12.5	10.3	12.7	12.5
Acacia mangium	8.3	6.7	7.0	8.3	6.7	7.0
Floristic and functional composition between leguminous trees (%)						
Leucaena leucocephala	40.2	42.2	41.2	39.1	38.5	38.1
Gliricidia sepium	25.1	25.1	22.1	19.7	20.3	18.9
Acacia mangium	23.1	23.1	21.1	22.1	20.1	19.5

Lowercase letters indicate differences among crops. Kruskal-Wallis test, $P < 0.05$.

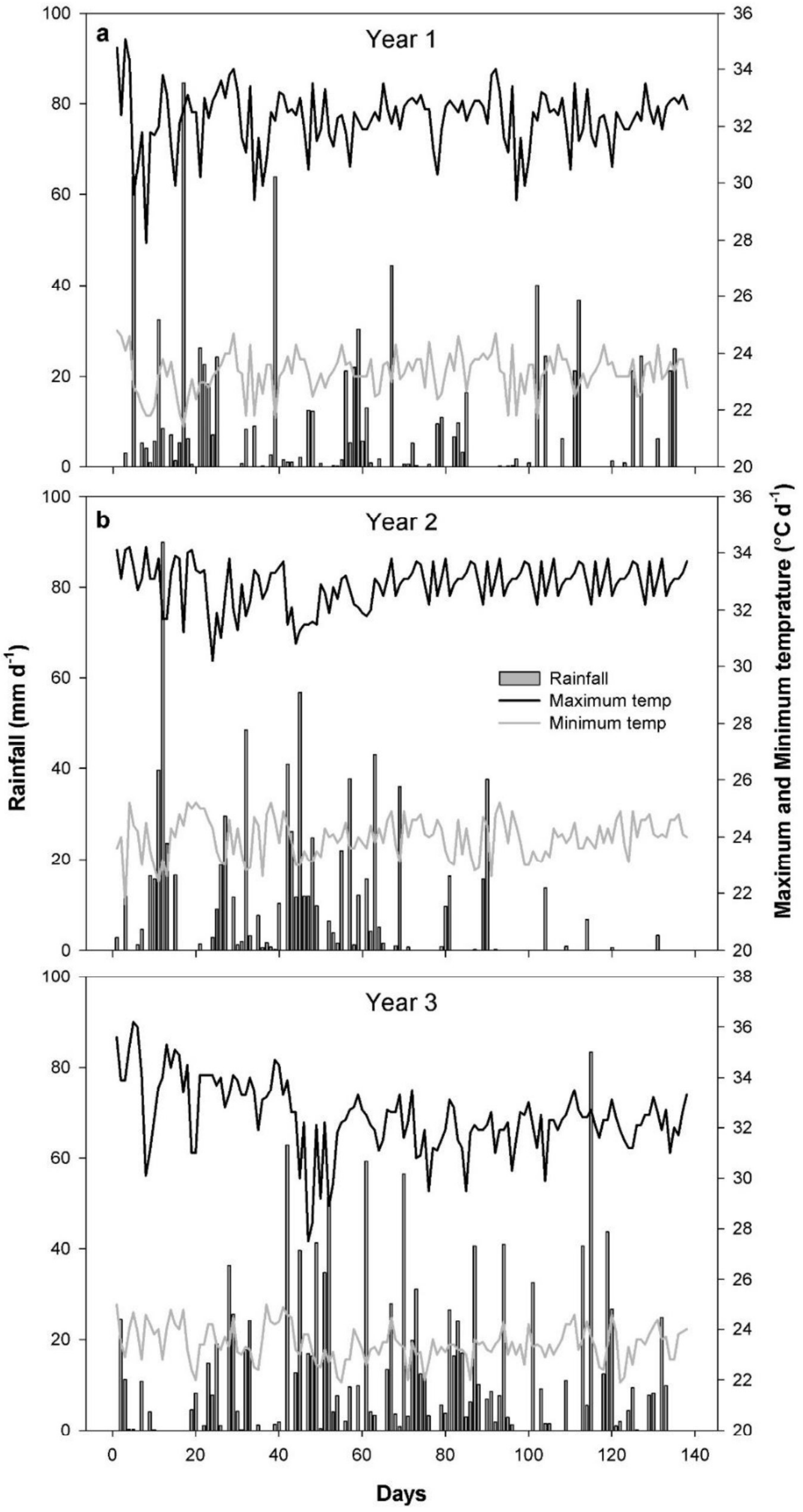

Fig. 1 Daily maximum and minimum temperatures (Temp) and rainfall growing three years from crop sowing (day 0) to harvesting (day 120).

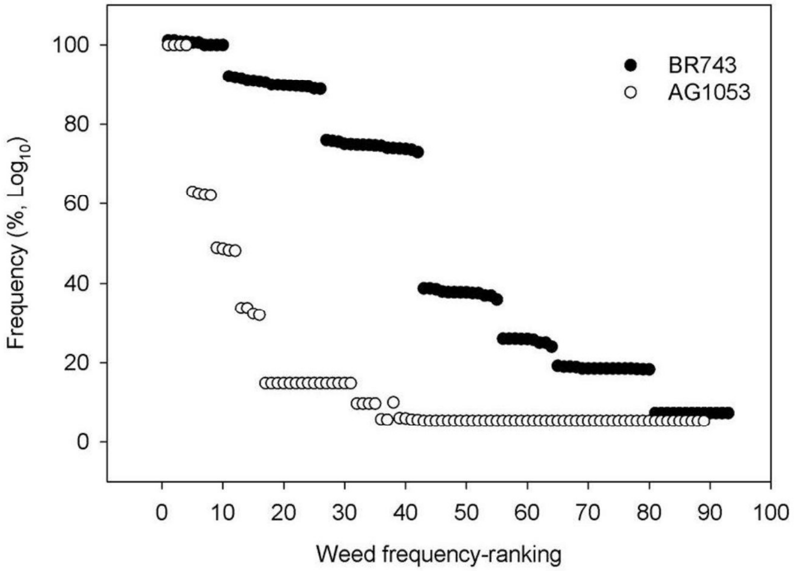

Figure 2. Percent frequency of weed species (log 10) as a function of the frequency ranking in the planting of corn

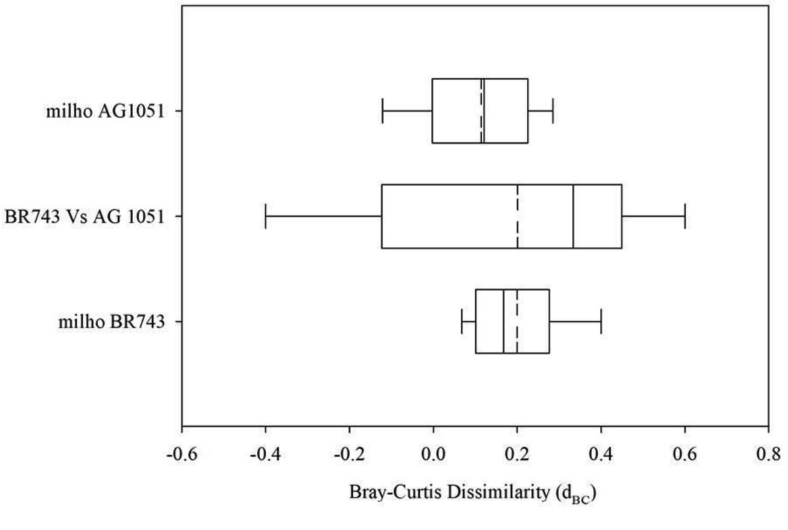

Figure 3. Box plots of the abundance-based Bray-Curtis dissimilarity (dBC) calculated to compare the species composition between both maize. Dotted line within boxes are mean values.