Effects of Fertilizer and Shade Management on Nitrogen Mineralization, Nitrifying Microbial Abundance and Nitrogen-Fixing Capacity of Erythrina poeppigiana in Coffee (Coffea arabica) Agroforestry Systems in Costa Rica

Stuart E. Barker III

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EFFECTS OF FERTILIZER AND SHADE MANAGEMENT ON NITROGEN MINERALIZATION, NITRIFYING MICROBIAL ABUNDANCE AND NITROGEN-FIXING CAPACITY OF *ERYTHRINA POEPPIGIANA* IN COFFEE (*COFFEA ARABICA*) AGROFORESTRY SYSTEMS IN COSTA RICA

by

STUART BARKER

(Under the Direction of Subhrajit Saha)

ABSTRACT

Worldwide chemical fertilizer use has increased by four times during the last 50 years. Conventional agricultural systems have a high nitrifying nature, resulting in a loss of nearly 70% of overall nitrogen (N) fertilizer inputs, an estimated economic loss of $81 billion. Over application of fertilizer is rampant in tropical developing nations in Central America, where coffee is major crop. Agroforestry offers ecologically sustainable land management strategies that promote the provision of ecosystem services such as, protection of biodiversity, climate change mitigation, and water and soil regulation. When legume trees are incorporated as the shade tree in coffee production, direct inputs of nitrogen can occur. The specific objectives of this study were, (1) to quantify the effects of inorganic fertilizer and shade treatments on soil organic carbon (SOC), (2) measure and quantify the mineralization rates under inorganic fertilizer and shade treatments, (3) determine if the spatial abundance of ammonia oxidizing bacteria (AOB) is affected by varying shade management, or by inorganic fertilizer treatment, and 4) measure the effects of inorganic fertilizer application on the transfer of biologically fixed N by *Erythrina poeppigiana* to *Coffea arabica* in agroforestry systems in the region. The field study was conducted in Aquiares, Costa Rica. Chemical fertilizer was applied between four treatments at the rate of 0, 110, 170, and 230 kg N ha⁻¹ yr⁻¹ and coupled with three shade treatments (no shade, managed shade, full shade) defined by the management strategies of the legume tree *E. poeppigiana*. Analyses showed no significant difference in total SOC by fertilizer and shade treatments. Measured NH₄⁺ μmol/L NH₄⁺ and NO₂⁻ + NO₃⁻ μmol/L NO₃⁻ concentrations differed significantly by the shade treatment, but net nitrogen mineralization rates were not significantly different by fertilizer or shade treatment. A significant difference in dsDNA copy number of AOB per soil g⁻¹ was determined by shade treatment. Finally, fertilizer treatment demonstrated a significant effect on the potential for biologically fixed nitrogen from *E. poeppigiana* to be transferred to coffee planted in association. Coffee agroforestry systems with full shade *E. poeppigiana* legume trees offered additional inputs of nitrogen to mitigate the use of chemical fertilizers.

INDEX WORDS: Agroforestry, Nitrogen dynamics, Nitrifying bacteria, Nitrogen mineralization, Fertilizer, Coffee production
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by

STUART BARKER
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by

STUART BARKER

Major Professor: Subhrajit Saha

Committee: John Schenk
Tiehang Wu

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CHAPTER 1
INTRODUCTION

With a projected 35% population increase by 2050, the globe faces a rise in demand for major crop production, challenged by climate change and food insecurity (Oyebamiji et al., 2015). Population growth is expected to plateau around 9 billion people, however, a major correlate of this deceleration in growth is increased wealth and purchasing power (Godfray et al., 2010). Increased population growth, coupled with higher purchasing power, leads to a greater demand for agricultural crops and commodities (Godfray et al., 2010). Overall crop production is predicted to increase by 50% to meet the anticipated demand over the next few decades (Doos, 2002). If conventional agricultural technologies and practices are used to meet the anticipated demand, further environmental degradation is inevitable (Tilman et al., 2002).

While working to increase crop production, we need to significantly decrease the climate impact of crop production (Smith et al., 2008). Agricultural practices release significant levels of CO$_2$, CH$_4$, and N$_2$O into the atmosphere. While considering direct and indirect emissions, agriculture contributes about 17-32% of the anthropogenic greenhouse gas (GHG) emissions that drive climate change (Smith and Gregory, 2013). Direct emissions of agriculture contribute between 5.1 and 6.1 Gt CO$_2$-eq, 10-12% of global GHG emissions, mainly in the form of CH$_4$ 3.3 Gt CO$_2$-eq yr$^{-1}$ and N$_2$O 2.8 Gt CO$_2$-eq yr$^{-1}$ (Smith and Gregory, 2013). However, the clearing of land and native vegetation for agricultural use releases large quantities of ecosystem carbon, such as CO$_2$ at 5.9 Gt CO$_2$-eq yr$^{-1}$ (sd 2.9) (Smith and Gregory, 2013). The production and use of chemical fertilizers is another important source of GHG emissions (Ingram et al., 2008).
The production of chemical fertilizers is energy intensive and contributes 0.3 to 0.6 Gt CO₂-eq/yr, roughly 0.6 to 1.2% of the world’s total GHG (Smith and Gregory, 2013). The largest source of GHG emissions from the use of chemical fertilizers is during their production, which emits CO₂ with current production methods (Tallaksen et al., 2015).

**Climate – Agriculture:**

CO₂ levels, temperature, and changing precipitation patterns will affect crop production (Parry et al., 2004). In particular, tropical and sub-tropical regions and associated developing countries are predicted to have deleterious impacts on agriculture in the wake of climate change (Ingram et al., 2008). While working to reduce the climate impact of crop production, it is important to consider the value of protecting freshwater resources, protecting biodiversity, and reducing the impact of food production on an array of ecosystem services. The ecosystem services framework has become a widely integrated framework to study the relationship between ecosystems and people (Fagerholm et al., 2016). The framework describes how ecosystems provide a variety of important benefits to human well-being and can influence decisions made towards mitigating ecosystem degradation (Fagerholm et al., 2016). The loss of ecosystem services that forests and natural ecosystems provide is attributed to the expansion of conventional agriculture (Wood et al., 2016). Biodiversity determines the functioning and properties of ecosystems and their ability to generate goods and ecosystem services (Hooper et al., 2005, Loreau et al., 2001). Diversifying agricultural ecosystems has been advocated to improve agricultural resiliency and sustainability (Allinne et al., 2016). Biodiversity sustains key ecological services, which can improve the ability of
agricultural ecosystems to internally maintain soil fertility, crop protection, and productivity (Altieri, 1999).

**Agroforestry:**

Agroforestry is a form of multiple cropping where two plant species exist that interact biologically, one of which is a woody perennial, and one of the species is managed for forage, annual or perennial crop production (Somarriba et al., 2001). Agroforestry offers ecologically sustainable land management strategies that promote the provision of ecosystem services (De Beenhouwer et al., 2013). Agroforestry is widely adopted in the world’s tropical and subtropical regions, and combines the provision of agricultural and forestry products with outputs such as, climate change mitigation, and water and soil regulation (Asase and Tetteh, 2016, Fagerholm et al., 2016). Agroforestry systems mimic natural ecosystems, promote carbon and nutrient cycles and improve sustainability in humid tropical agriculture (Munroe et al., 2015). Tropical forests are among the most biodiverse ecosystems on Earth, providing essential ecosystem services to the benefit of society (Wright, 2005, Gardner et al., 2009). In the past century, tropical forests have been subjected to dramatic changes through anthropogenic land conversion, largely resulting from a shift to agricultural land (Lambin et al., 2003). From 2010 to 2015, tropical forest area declined at a rate of 5.5 M ha y$^{-1}$ (Keenan et al., 2015). Tropical agroforestry systems have been proposed as a way to sustain biodiversity and the associated ecosystem services such as, buffering of climatic extremes and enhancing soil productivity (De Beenhouwer et al., 2013). In an analysis of biodiversity and ecosystem services benefits in coffee agroforestry, De Beenhour (2013) reported response ratios of forest species richness and total species richness were significantly
lower in the more intensively managed than in more natural land use categories; with a decline of -46% when comparing agroforest with plantation, and -11% when comparing forest with agroforest.

*Coffee:*

Coffee (*Coffea arabica*) is one of the most valuable agricultural exports from developing nations, employing over 25 million people worldwide, and is cultivated in some of the world’s most biodiverse regions (Ricketts *et al.*, 2004). Full sun, monoculture, coffee production produces high economic yields using dwarf-type high yielding varieties, with high planting densities (Lopez-Rodriguez *et al.*, 2015). Higher yields are attributed to increased photosynthetic expression of the coffee plant (Lopez-Rodriguez *et al.*, 2015). While full sun production can produce higher yields under optimal climatic conditions, it comes at the expense of high production cost, loss of biodiversity, increased nutrient run-off, and the reduction in the provision of ecosystem services. (Munroe *et al.*, 2015, Jha *et al.*, 2014). Incorporating shade trees in coffee production can provide an array of benefits. Shade trees can diminish crop exhaustion, increase longevity of coffee plants, improve soil fertility, and provide timber value, along with the provision of fruits and other products (Beer *et al.*, 1997).

In an effort to improve their gross national income, many Latin American countries underwent a technological transformation of traditional agroecosystems in order to maximize coffee yields, production and profits for an export market (Castro-Tanzi *et al.*, 2014). In Costa Rica, ranked in the top 15 coffee producing countries between 2000 and 2009, this transformation resulted in a near elimination of the shade tree canopy, increased planting densities of high-yielding varieties, and increased use of
agrochemicals, without proper consideration and evaluation of the ecological consequences (Castro-Tanzi et al., 2014). Intensively managed coffee (Coffea arabica) systems in Costa Rica, grown under heavily pruned leguminous trees or in unshaded monocultures that receive high fertilization rates (~250 kg N ha\(^{-1}\) yr\(^{-1}\)), are a suspected cause of the increased ground water nitrate (NO\(_3^-\)) concentration in the Central Valley (Harmand et al., 2007). Additionally, intensive fertilizer use can lead to an increase in exchangeable acidity, and a decrease in cation exchange capacity (Barak et al., 1997), which can lead to yield reductions because of soil acidification over time (Matsuyama et al., 2005). Moreover, chemical fertilizer use in conventional coffee production can account for up to 55% of total variable costs for farmers (Lyngbaek et al., 2001). Therefore, moderate reductions in chemical fertilizer use may provide a cost saving mechanism that can improve environmental performance without dramatic reductions to yield (Castro-Tanzi et al., 2014).

**Nitrogen dynamics:**

Above and below-ground nitrogen (N) transfer from leguminous shade trees to the coffee crop is an important N source in agroforestry systems (Chesney, 2008, Isaac et al., 2012, Munroe and Isaac, 2014). When legume trees are incorporated as the shade tree, direct inputs of N occur through mycorrhizal fungi networks or absorption of N-rich root exudates of the legume tree by the coffee plant (Chesney and Nygren, 2002), (Nygren and Leblanc, 2015). The amounts of N contributed will depend on the factors that limit N fixation, which include: limited nutrient supply; inappropriate symbionts; nodule effectiveness and activity; moisture supply; and presence of inhibitors, such as combined nitrogen (Munroe and Isaac, 2014). Castro-Tanzi et al. (2014) reported N
contributions of 24 ± 3.3% from biological N$_2$ fixation when coffee was grown in association with tree species of the genera *Erythrina*; however, with the facilitation of organic and inorganic forms of N being dependent on soil microbial communities, it is of interest to study the factors affecting spatial availability of usable N to crops (Hayatsu *et al.*, 2008).

The microbial process of nitrification is a key and integral part of the soil N cycle, which influences the fate of N in terrestrial systems (Ouyang *et al.*, 2016). Inorganic N forms such as, NH$_4^+$ or NO$_3^-$, are major forms of N uptake for plants in agricultural systems (Subbarao *et al.*, 2013). The biological oxidation of ammonia (NH$_3$) or ammonium (NH$_4^+$) to NO$_3^-$ is mediated by ammonia-oxidizing archaea (AOA), ammonia-oxidizing bacteria (AOB), and the nitrite-oxidizing bacteria (NOB) groups (Hayatsu *et al.*, 2008, Ouyang *et al.*, 2016). The first step of the nitrification process is the oxidation of NH$_3$ or NH$_4^+$ to hydroxylamine (H$_3$NO) and nitrite (NO$_2^-$), and this step is catalyzed by the AOA and AOB groups (Ouyang *et al.*, 2016). The last nitrification step is the oxidation of NO$_2^-$ to NO$_3^-$ and is performed by the NOB group (Wertz *et al.*, 2008). Some studies suggest AOB are more dominant over AOA in agricultural soils, but conflicting reports suggest the abundance and activity of AOA and AOB are affected by environmental conditions such as, ammonium (NH$_4^+$) concentration, N availability, temperature, salinity, moisture, pH, soil organic matter, and pH (Zhou *et al.*, 2016).

In agricultural systems, rapid nitrification rates result in inefficient N use by crops, leading to increased leaching and environmental pollution (Subbarao *et al.*, 2013). Natural ecosystems exploit various N forms (organic and inorganic) and utilize multiple pathways to regulate N flows, restricting N flow solely through the nitrification path.
(Smolander et al., 1998). By utilizing leguminous shade trees in coffee production, the total N pool can be supplemented by biologically fixed N and organic N forms from leaf litter and root turnover (Chesney and Nygren, 2002). Additionally, forms of ammonium based fertilizers could reduce the amount of leaching and N pollution over NO$_3^-$, as NH$_4^+$ is much less mobile in the soil than NO$_3^-$ and, therefore, has a longer N retention time in the root zone of plants, increasing the time for uptake (Subbarao et al., 2013).

In this study, I sought to evaluate the N supply and dynamics in coffee (Coffea arabica) agricultural systems under different management constraints, ranging from intensively managed no-shade monoculture production, to less intensively managed full-shade agroforestry systems. The study was conducted in the central-Caribbean region of Costa Rica, in an experimental designation within the Aquiares coffee farm, a Rainforest Alliance™ certified farm, characterized by andisol soils (Taugourdeau et al., 2014). The experiment was carried out in a split-plot design. Urea-based fertilizers were applied between four treatments at the rate of 0, 110, 170, 230 kg N ha$^{-1}$ yr$^{-1}$. Each fertilizer treatment plot contained three shade affects. The first being characterized by the absence of the legume tree E. poeppigiana (no shade monoculture, NS), the second having pruned E. poeppigiana (managed shade, MS), and the third having free-growing E. poeppigiana (full-shade, FS).

The specific objectives of this study were:

1) To quantify the effects of inorganic fertilizer and shade treatments on soil organic carbon (SOC).

2) To measure and quantify the mineralization rates under inorganic fertilizer and shade treatments.
3) To determine if the spatial abundance of AOB is affected by varying shade management, or by inorganic fertilizer treatment.

4) To measure the effects of inorganic fertilizer application on the transfer of biologically fixed N by *E. poeppigiana* to *Coffea arabica* in agroforestry systems in the region.
FIELD STUDY

Study location:

The study was conducted in the central-Caribbean country of Costa Rica, in one of the largest coffee farms in the country, the Aquiares farm (9° 56’ 19” N, 83° 43’ 46” W) (660 ha), “Rainforest Alliance™” certified, located 15 km from CATIE (Centro Agronómico Tropical de Investigación y Enseñanza) (Taugourdeau et al., 2014). The Aquiares farm is 1020 m above sea level on the slopes of the Turrialba Volcano, with soils belonging to the order of andisols (USDA, 1999). Andisols are soils that develop from volcanic material, with high organic matter and allophane content and high infiltrability (Benegas et al., 2014, Taugourdeau et al., 2014). The Köppen-Geiger climate classification ranks the climate of the area as tropical humid with no dry season (Peel et al., 2007). The mean annual rainfall at the Aquiares farm between 1973–2009 was 3014 mm, with the driest month being March (123 mm), and the wettest month being December (329 mm) (Taugourdeau et al., 2014). The Aquiares farm is planted with coffee (Coffea arabica L. var. caturra) with an initial planting density of 1.11 m on the row and 1.43 m in-between rows, with 2 coffee stumps per position, about 6300 positions ha⁻¹.
Figure 1. Map of Costa Rica including the province of Cartago, city of Turrialba and an aerial view of the field study site in the Aquiares farm (Google Maps, last accessed March 2017).

**Site description and experimental design:**

The experiment was conducted in a four-year old experimental agroforestry site located within the Aquiares farm. The experimental site is four hectares, which is divided into 12 experimental plots (~ 0.3 ha each) that differ by fertilizer and shade management.
practices. The experimental site was fashioned in a split-plot design, where each whole plot received a fertilizer treatment and contained three subplot shade treatments within. Urea fertilizer was applied between four treatments at the rate of 0, 110, 170, and 230 kg N ha\(^{-1}\) yr\(^{-1}\). The three shade treatments were defined by the management strategies of the legume tree *E. poeppigiana*, planted in association with the coffee crop. The shade treatments consisted of 1) no shade, full sun monoculture, where *E. poeppigiana* is present; 2) managed shade, where *E. poeppigiana* is fully pruned twice per year; and 3) full shade, where *E. poeppigiana* is free growing. The average height of pruned *E. poeppigiana* was about 4–5 m, while average height of free-growth *E. poeppigiana* was 30–33 m.

Having three shade treatments split within four fertilizer treatments allowed for 12 treatment combinations, which were replicated 3 times, totaling 36 subplots. The four fertilizer treatments were distributed at random amongst the 12 plots.
Figure 2. Map of experimental site, includes fertilizer treatments by block (kg N ha\(^{-1}\)y\(^{-1}\)) and shade management within each block (no shade, managed shade, full shade). Boxes within each plot indicate subplots containing shade treatments. Circles indicate full growth *Erythrina* trees.

*Note: The full shade treatment in plot number 2 was excluded from all analyses. The full shade tree in subplot number 2 was struck by lightning and was removed.

<table>
<thead>
<tr>
<th>Whole plot numbers</th>
<th>Fertilizer treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>2, 6, 8</td>
<td>0</td>
</tr>
<tr>
<td>1, 4, 9</td>
<td>110</td>
</tr>
<tr>
<td>10, 11, 12</td>
<td>170</td>
</tr>
<tr>
<td>3, 5, 7</td>
<td>230</td>
</tr>
</tbody>
</table>

**Table 1. Fertilizer treatments were applied to the whole plot in a completely randomized design (kg N ha\(^{-1}\)y\(^{-1}\)).**

**Statistical analyses:**

All statistical analyses were completed using JMP 12 (Cary, NC). Analysis of variance under a split–plot design was used for data that fit a normal distribution for SOC Mg ha\(^{-1}\), total NH\(_4\)\(^+\) and NO\(_3\)\(^-\) µmol /L, N mineralization rates, and dsDNA copy number of AOB per soil g\(^{-1}\) under fertilizer treatments (0, 110, 170, and 230 kg N ha\(^{-1}\) y\(^{-1}\)) and shade treatments (no shade, managed shade, and full shade). Connecting letters reports were generated by Tukey’s HSD. Analysis of mean \(\delta^{15}N\) was carried out by analysis of covariance between distances (1, 2, 3, 4, 6 and 10 m) from managed *Erythrina* trees and fertilizer treatments (0 and 230 kg N ha\(^{-1}\) y\(^{-1}\)).
**Total Soil Organic Carbon Analysis:**

Two sets of four soil-cores were taken from each subplot to 20 cm in depth with a 0.5 L soil auger and combined to form a composite sample. Soil cores were taken from the center of each subplot to avoid edge effect from neighboring treatments. After collection, composite samples were dried in a drying oven for 72 hours at 60° C. Once dried the soils were sieved at 2 mm to remove gravels and plant material. To process the soil samples for total nitrogen (TN) and total carbon (TC) analysis, the size of the soil granules required further reduction. The soil samples were placed in scintillation vials with two ceramic beads and ground for 5 minutes using a SPEX Prep Mixer/Mill 8000k (Metuchen, NJ). A Thermo Scientific Flash 2000 TN/TC Soil Analyzer (Waltham, MA) was used to assess the samples for TC content. Total SOC was calculated by using the following formula (Eq. 1), calculating total SOC in Mg ha⁻¹ (Saha et al., 2010):

**Equation 1:**  \[ C \text{ storage} = C \text{ concentration} \times BD \times \text{Soil Depth} \times \text{Fraction weight} \]

Where:
- C storage = Mass measured in Mg ha⁻¹ (Mg = megagram)
- C concentration = g per kg of soil contained in sample
- BD = Bulk density (Mg m⁻³)
- Depth = Depth of soil profile (cm)
- Fraction weight = Percent of the fraction in the sample

**N mineralization rates:**

Composite soil cores from each subplot were used for total NH₄⁺ µmol /L NH₄⁺ and NO₂⁻ + NO₃⁻ µmol /L NO₃⁻ and net N mineralization rate analyses. Composite soil samples were taken (0–20 cm) directly from the field to the lab at CATIE for NO₃⁻ and NH₄⁺ extractions. Once in the lab, 50 g of soil was weighed for each extraction. For each subplot, an initial and final subsample of soil was taken to calculate total NO₃⁻ and NH₄⁺
concentration and net N mineralization rates over time. Initial subsamples underwent NO$_3^-$ and NH$_4^+$ extraction immediately by 2M KCL and were stored until laboratory analysis. Final subsamples were sealed with parafilm and placed in an incubation chamber at 25°C for 14 days before undergoing NO$_3^-$ and NH$_4^+$ extraction with 2M KCL. Liquid NO$_3^-$ and NH$_4^+$ extraction samples were preserved in vacuum sealed sample tubes and shipped to CIRAD (Centre de Coopération Internationale en Recherche Agronomique pour le Développement, Avenue Agropolis, 34398 Montpellier Cedex 5 France) for total NH$_4^+$ µmol /L NH$_4^+$ and NO$_2^-$ + NO$_3^-$ µmol /L NO$_3^-$ calculation and analyses. Net N mineralization was calculated as the change in (NH$_4^+$ µmol /L NH$_4^+$) + (NO$_2^-$ + NO$_3^-$ µmol /L NO$_3^-$) during the 14 day incubation (Neill et al., 1997).

*Nitrifying Bacteria Analysis:*

Composite soil sampling was used to quantify the microbial communities of the plots. Composite samples were taken in each subplot (n = 70) to 20 cm using a 0.5 L auger. Composite samples were taken within the same day and immediately taken to the lab space in CATIE and stored in the freezer at approximately -5°C for 10 hours. The following morning, samples were vacuum freeze-dried at -52°C for DNA preservation. Soil microbial DNA extractions were performed using a PowerSoil DNA Isolation kit (MO BIO, Carlsbad, CA, USA).

Quantitative polymerase chain reaction (qPCR) was used for absolute DNA quantification of the target AOB microbial group. The qPCR methods established by Jin et al., 2010 were followed for target group quantification. qPCR was performed using the QuantStudio™ 6 Flex Real-Time PCR System (Life Technologies, Carlsbad, CA, USA) with SYBR-Green I fluorescent dye. All PCR mixtures used recommended 20 µl
protocol for SYBR consisting of 10 µl of 2X PCR Master Mix, 0.4 µl of 10 µM forward and reverse primers, 5 µl of isolated DNA, and 4.2 µl of nuclease-free water. We utilized AOB target primer sets by Rotthauwe et al., 1997; Table 2. The AOB amoA PCR program included 10 min at 95° C; 40 cycles of 30 s at 95° C, 1 min at 57° C, and 1 min at 72° C; and a final elongation step at 72° C for 10 seconds. Melting curve confirmation analysis was conducted for all reactions to ensure the correct target amplification. Standards for the AOB primer set were created from DNA isolated from soil (Moore et al., 2016). Product bands were excised from agarose gels then extracted and purified using a QIAquick Gel Extraction Kit (Qiagen, Hilden, Germany). The resulting fragments were ligated into TOPO vectors and cloned into TOP10 competent cells (Life Technologies, Carlsbad, CA) using manufacturer protocols. Plasmids were extracted from the resulting culture using QIAPrep Spin Miniprep Kits (Qiagen, Hilden, Germany) and plasmid concentrations were quantified using a NanoDrop ND-1000 UVeVis spectrophotometer (NanoDrop Technologies, Wilmington, DE, USA). Ten-fold serial dilutions were used to create standard sets (ranging from 1.5 x 10^2 to 1.54 x 10^8 dsDNA copy number soil g⁻¹). Average standard curve efficiencies were 92.65% with an r^2 > 0.98. The following formula was used to absolute quantification of AOB:

Number of copies (molecules) = \frac{X \times 6.0221 \times 10^{23} \text{molecules/mole}}{(N \times 660\text{g/mole}) \times 1 \times 10^9 \text{ng/g}}

Where:
X = amount of amplicon (ng)
N = length of dsDNA amplicon
660 g/mole = average mass of 1 bp dsDNA
Table 2. Primers used for qPCR amplification

<table>
<thead>
<tr>
<th>Target gene</th>
<th>Primer</th>
<th>Sequence (5'-3')</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>amoA</td>
<td>amoA-1F</td>
<td>GGGGTTTCTACTGGTGGT</td>
<td>Rothhauwe et al., 1997</td>
</tr>
<tr>
<td></td>
<td>amoA-2R</td>
<td>CCCCTCKGSAAAGCCTTCTTC</td>
<td>Rothhauwe et al., 1997</td>
</tr>
</tbody>
</table>

**N-Fixing Capacity:**

Two stable isotopes of N exist, $^{14}$N and $^{15}$N. The heavy isotope, $^{15}$N, occurs in atmospheric N$_2$ at a constant of 0.3663 atoms % (Dawson *et al.*, 2002). N$_2$ exists in a range of abundances within soil, typically at an enriched abundance (Munroe *et al.*, 2014). If a sample is compared to an absolute abundance ratio derived from atmospheric N, researchers can obtain a delta (δ) $^{15}$N value (Martinelli *et al.*, 1999, Dawson *et al.*, 2002). A sample enriched in $^{15}$N relative to natural abundance would be an example of a positive δ$^{15}$N value; in contrast a negative δ$^{15}$N would be associated with lower $^{15}$N (Dawson *et al.*, 2002). When small δ$^{15}$N values are compared with a non-N$_2$-fixing reference plant with larger δ$^{15}$N values, enrichment of available soil N is taking place, and can be used to quantify the percentage of N derived from the atmosphere by N$_2$-fixing plants via the natural abundance method (Munroe *et al.*, 2014).

The natural $^{15}$N abundance method was used to calculate if there is variation in the N fixing capacity of *E. poeppigiana* by fertilizer treatment. Sample plots 2, 3, 5, 6, 7 and 8 were utilized to compare biological N$_2$ fixation by *E. poeppigiana*. Plots 2, 6, and 8 formed the control group with no inorganic fertilizer application and 3, 5, and 7 formed the treatment group with an application of 230 kg N ha$^{-1}$y$^{-1}$ of ammonia fertilizer.

To determine whether the N$_2$-fixing capacity of *E. poeppigiana* is affected by fertilizer application and at what distance from *E. poeppigiana* does *C. arabica* L. var.
caturra receive fixed N, composite leaf samples (n = 84) were taken. Two E. poeppigiana trees (n = 12) were selected from each plot and two transects along the planted C. arabica L. var. caturra rows were created, sampling at specified distances (1, 2, 3, 4, 6, 10 m) from the E. poeppigiana trees. Ten mature leaves from each E. poeppigiana trees were selected, dried for 48 hours at 60° C and ground to form a composite sample. Forty mature coffee leaves (identified with assistance from an experienced farm manager) were selected from each C. arabica L. var. caturra plant, dried for 48 hours at 60° C, and grind to form a composite sample. Leaf samples were then sealed in centrifuge vials and transported to the SISSIL (Skidaway Institute Scientific Stable Isotope Laboratory, Savannah, GA, USA) for $^{15}$N analyses.
No significant difference for SOC Mg ha$^{-1}$ was detected between treatments of fertilizer, shade, or shade crossed with fertilizer (p= 0.3765, 0.9878, 0.6464, Table 3).

**Table 3. Analysis of variation of total SOC Mg ha$^{-1}$ under fertilizer treatment (0, 110, 170, 230 kg N ha$^{-1}$ y$^{-1}$) and shade treatment (no shade, managed shade, and full shade).**

<table>
<thead>
<tr>
<th>Soil Organic Carbon Mg ha$^{-1}$</th>
<th>Whole Plot</th>
<th>DF</th>
<th>Mean square</th>
<th>F Ratio</th>
<th>Prob. &gt; F</th>
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<tbody>
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<td>Fertilizer Treatment</td>
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<td>1.1799</td>
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</tr>
<tr>
<td>Error</td>
<td>8</td>
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<td>14.3215</td>
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</table>

<table>
<thead>
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<th>Subplot</th>
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<th>Mean square</th>
<th>F Ratio</th>
<th>Prob. &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shade</td>
<td>2</td>
<td>3.4611</td>
<td>0.0123</td>
<td>0.9878</td>
</tr>
<tr>
<td>Shade Treatment *Fertilizer Treatment</td>
<td>6</td>
<td>199.747</td>
<td>0.7109</td>
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</tr>
<tr>
<td>Error</td>
<td>15</td>
<td>281</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Indicates significance
Figure 3. Total SOC Mg ha\(^{-1}\) by fertilizer treatment (0, 110, 170, 230 kg N ha\(^{-1}\) y\(^{-1}\)).

Treatments not connected by the same letter are significantly different. Each error bar is constructed using 1 standard error from the mean.
Figure 4. Total SOC Mg ha$^{-1}$ by shade treatment (no shade, managed shade, and full shade). Treatments not connected by the same letter are significantly different. Each error bar is constructed using 1 standard error from the mean.
No significant difference for the fertilizer and shade crossed with fertilizer treatments were detected (p= 0.9455, 0.5467). A significant difference in mean NH$_4^{+}$ µmol/L NH$_4^{+}$ for the shade treatment was detected. (p= 0.0262, Table 4).

Table 4. Analysis of variance of NH$_4$ µmol/L NH$_4$ under fertilizer treatment (0, 110, 170, 230 kg N ha$^{-1}$ y$^{-1}$) and shade treatment (no shade, managed shade, and full shade).

NH$_4^{+}$ µmol/L NH$_4^{+}$

<table>
<thead>
<tr>
<th>Whole Plot</th>
<th>DF</th>
<th>Mean square</th>
<th>F Ratio</th>
<th>Prob&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Error</td>
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<table>
<thead>
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<th>F Ratio</th>
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</thead>
<tbody>
<tr>
<td>Shade</td>
<td>2</td>
<td>19.7611</td>
<td>4.6879</td>
<td>0.0262*</td>
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<tr>
<td>Shade Treatment *Fertilizer Treatment</td>
<td>6</td>
<td>3.61645</td>
<td>0.8579</td>
<td>0.5467</td>
</tr>
<tr>
<td>Error</td>
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<td>4.2153</td>
<td>4.22</td>
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</tr>
</tbody>
</table>

*Indicates significance
Figure 5. Total NH$_4^+$ μmol/L NH$_4^+$ by fertilizer treatment (0, 110, 170, 230 kg N ha$^{-1}$ y$^{-1}$). Treatments not connected by the same letter are significantly different. Each error bar is constructed using 1 standard error from the mean.
Figure 6. Total NH$_4^+$ µmol/L NH$_4^+$ by shade treatment (no shade, managed shade, and full shade). Treatments not connected by the same letter are significantly different. Each error bar is constructed using 1 standard error from the mean.
No significant difference for the fertilizer and shade crossed with fertilizer treatments were detected (p= 0.5472, 0.2496). A significant difference in mean $\text{NO}_2^- + \text{NO}_3^-$ µmol/L $\text{NO}_3^-$ for the shade treatment was detected. (p= 0.0003, Table 5).

**Table 5. Analysis of variance of $\text{NO}_2^- + \text{NO}_3^-$ µmol/L $\text{NO}_3^-$ under fertilizer treatment (0, 110, 170, 230 kg N ha$^{-1}$ y$^{-1}$) and shade treatment (no shade, managed shade, and full shade).**

<table>
<thead>
<tr>
<th>Whole Plot</th>
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<th>Mean square</th>
<th>F Ratio</th>
<th>Prob&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fertilizer Treatment</td>
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<td>1769.23</td>
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<td>Error</td>
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<td>2345.2</td>
<td>2.5649</td>
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</tr>
<tr>
<td>Shade</td>
<td>2</td>
<td>13396.5</td>
<td>14.6511</td>
<td>0.0003*</td>
</tr>
<tr>
<td>Shade Treatment * Fertilizer Treatment</td>
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<td>1356.25</td>
<td>1.4833</td>
<td>0.2496</td>
</tr>
<tr>
<td>Error</td>
<td>15</td>
<td>914.36</td>
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</table>

*Indicates significance
Figure 7. Total NO₂⁺+NO₃⁻ μmol/L NO₃⁻ by fertilizer treatment (0, 110, 170, 230 kg N ha⁻¹ y⁻¹). Treatments not connected by the same letter are significantly different. Each error bar is constructed using 1 standard error from the mean.
Figure 8. Total NO$_2^-$+NO$_3^-$ µmol/L NO$_3^-$ by shade treatment (no shade, managed shade, and full shade). Treatments not connected by the same letter are significantly different. Each error bar is constructed using 1 standard error from the mean.
No significant difference for net N mineralization rates was detected between treatments of fertilizer, shade, or shade crossed with fertilizer (p= 0.6658, 0.9612, 0.193, Table 6).

**Table 6. Analysis of variance of net N mineralization rates under fertilizer treatment (0, 110, 170, 230 kg N ha\(^{-1}\) y\(^{-1}\)) and shade treatment (no shade, managed shade, and full shade).**

**Net N Mineralization**

<table>
<thead>
<tr>
<th>Whole Plot</th>
<th>DF</th>
<th>Mean square</th>
<th>F Ratio</th>
<th>Prob&gt;F</th>
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<tbody>
<tr>
<td>Fertilizer Treatment</td>
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<td>6.05709</td>
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<tr>
<td>Error</td>
<td>8</td>
<td>11.2513</td>
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<table>
<thead>
<tr>
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<th>F Ratio</th>
<th>Prob&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shade</td>
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<td>0.05634</td>
<td>0.0397</td>
<td>0.9612</td>
</tr>
<tr>
<td>Shade Treatment *Fertilizer Treatment</td>
<td>6</td>
<td>2.39173</td>
<td>1.684</td>
<td>0.193</td>
</tr>
<tr>
<td>Error</td>
<td>15</td>
<td>1.42027</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Indicates significance
Figure 9. Net N mineralization rates by fertilizer treatment (0, 110, 170, 230 kg N ha\(^{-1}\) y\(^{-1}\)). Treatments not connected by the same letter are significantly different. Each error bar is constructed using 1 standard error from the mean.
Figure 10. Net N mineralization rates by shade treatment (no shade, managed shade, and full shade). Treatments not connected by the same letter are significantly different. Each error bar is constructed using 1 standard error from the mean.
No significant difference in dsDNA copy number of AOB per soil g⁻¹ for the fertilizer and shade crossed with fertilizer treatments were detected (p= 0.8345, 0.8971).

A significant difference in dsDNA copy number of AOB per soil g⁻¹ for the shade treatment was detected. (p= 0.0166, Table 7).

Table 7. Analysis of variance of dsDNA copy number of AOB per soil g⁻¹ under fertilizer treatment (0, 110, 170, 230 kg N ha⁻¹ y⁻¹) and shade treatment (no shade, managed shade, and full shade).

dsDNA copy number of AOB per soil g⁻¹

<table>
<thead>
<tr>
<th>Whole Plot</th>
<th>DF</th>
<th>Mean square</th>
<th>F Ratio</th>
<th>Prob&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fertilizer Treatment</td>
<td>3</td>
<td>7.66E+07</td>
<td>0.2858</td>
<td>0.8345</td>
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<tr>
<td>Error</td>
<td>8</td>
<td>2.67E+08</td>
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<table>
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<th>Subplot</th>
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<th>Prob&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shade</td>
<td>2</td>
<td>1.76E+09</td>
<td>5.4532</td>
<td>0.0166*</td>
</tr>
<tr>
<td>Shade Treatment *Fertilizer Treatment</td>
<td>6</td>
<td>1.14E+08</td>
<td>0.3531</td>
<td>0.8971</td>
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<tr>
<td>Error</td>
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</table>

*Indicates significance
Figure 11. dsDNA copy number of AOB per soil g⁻¹ under fertilizer treatment (0, 110, 170, 230 kg N ha⁻¹ y⁻¹). Treatments not connected by the same letter are significantly different. Each error bar is constructed using 1 standard error from the mean.
Figure 12. dsDNA copy number of AOB per soil g$^{-1}$ by shade treatment (no shade, managed shade, and full shade). Treatments not connected by the same letter are significantly different. Each error bar is constructed using 1 standard error from the mean.
Analysis of the interaction between distances (1, 2, 3, 4, 6 and 10 m) from managed *Erythrina* trees and fertilizer treatments (0 and 230 kg N ha\(^{-1}\) y\(^{-1}\)) on mean \(\delta^{15}\)N was compared. No significant difference for the interaction between distance and fertilizer treatments was detected (\(p= 0.5389\), Table 8). Thus, a full ANCOVA could be performed.

Table 8. Analysis of the interaction between distance (1, 2, 3, 4, 6 and 10 m) from managed *Erythrina* trees and fertilizer treatments (0 and 230 kg N ha\(^{-1}\) y\(^{-1}\)) on mean \(\delta^{15}\)N in mature *Coffea arabica* leaf samples.

<table>
<thead>
<tr>
<th>Mean (\delta^{15})N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effects Test</td>
</tr>
<tr>
<td>Fertilizer Treatment</td>
</tr>
<tr>
<td>Distance</td>
</tr>
<tr>
<td>Distance *Fertilizer Treatment</td>
</tr>
</tbody>
</table>

Analysis of mean \(\delta^{15}\)N was carried out by ANCOVA between distances (1, 2, 3, 4, 6 and 10 m) from managed *Erythrina* trees and fertilizer treatments (0 and 230 kg N ha\(^{-1}\) y\(^{-1}\)). No significant difference for the distance effect was determined (Prob>F 0.4724). Significant difference in mean \(\delta^{15}\)N between fertilizer treatments was detected (\(p= 0.0022\), Table 9).

Table 9. Analysis of covariance by distance (1, 2, 3, 4, 6 and 10 m) from managed *Erythrina* trees and fertilizer treatment (0 and 230 kg N ha\(^{-1}\) y\(^{-1}\)) on mean \(\delta^{15}\)N in mature *Coffea arabica* leaf samples.

<table>
<thead>
<tr>
<th>Mean (\delta^{15})N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effects Test</td>
</tr>
<tr>
<td>Fertilizer Treatment</td>
</tr>
<tr>
<td>Distance</td>
</tr>
</tbody>
</table>

*Indicates significance
Figure 13. Regression plot of mean δ^{15}N in coffee leaves with no fertilizer treatment (0 kg N ha^{-1} y^{-1}) and distance from the managed *Erythrina* tree (1, 2, 3, 4, 6 and 10 m).
Figure 14. Regression plot of mean $\delta^{15}\text{N}$ in coffee leaves with fertilizer treatment (230 kg N ha$^{-1}$ y$^{-1}$) and distance from the managed Erythrina tree (1, 2, 3, 4, 6 and 10 m).
CHAPTER 4
DISCUSSIONS

The primary objectives of this study were to examine how inorganic fertilizer application and the intercropping and management of *E. poeppigiana* affect soil organic carbon and nitrogen dynamics in coffee agroforestry systems in Costa Rica. While the effects of fertilizer application on crop yield and mineralization rates in coffee agricultural systems have been well studied, the effects of inorganic fertilizer application and the intercropping of *E. poeppigiana* in coffee agroforestry systems on SOC, N mineralization rates and nitrifying bacteria abundance is relatively understudied. This study evaluated fertilizer treatments (0, 110, 170 and 230 kg N ha\(^{-1}\) y\(^{-1}\)) in relation to varying rates of shade treatments (no shade, managed shade, full shade), characterized by the management style of *E. poeppigiana* planted amongst the main coffee crop.

Treatments of fertilizer coupled with shade management practice of *E. poeppigiana* did not significantly affect SOC in Mg ha\(^{-1}\) at the 0-20 cm soil depth. A higher rate of fertilizer application along with full-growth *Erythrina* trees was predicted to show a significant increase in the amount of soil organic carbon being sequestered in the 0-20 cm soil layer when compared to low fertilizer, full sun treatments. Christopher and Lal, 2007 reported higher crop production in response to mineral N fertilizer application results in greater root exudates and more crop residues, therefore enhancing SOC sequestration in agricultural soils. Although, the addition of N has also been reported to have a negative, or no effect on SOC sequestration (Mack *et al.*, 2004). In this study, the treatment of fertilizer, the treatment of shade, or the interaction of the two treatments did not significantly affect total SOC Mg ha\(^{-1}\) in the 0-20 cm soil layer. Leaf
litter accumulation on the ground was observed to be highest amongst the full shade treatment, due to the large amount of leaf deposition from the full-growth *Erythrina* trees intercropped with the coffee crop. While the addition of rich organic matter can be a significant attribute to increasing total SOC, the results of this study would suggest that the amount of organic matter being contributed by the *Erythrina* trees was not enough to cause a significant difference in total SOC (Gentile *et al.*, 2010).

The measurement of total NH$_4^+$ and NO$_2^-$ + NO$_3^-$ by fertilizer and shade treatment were not significantly different by the fertilizer treatment, but did yield significantly different results by the shade treatment. The hypothesis was that the presence of the *Erythrina* trees would contribute additional N through organic material deposition and biological N fixation, ultimately increasing NH$_4^+$ and NO$_2^-$ + NO$_3^-$ concentrations. In calculating total NH$_4^+$ and NO$_2^-$ + NO$_3^-$, the highest concentrations were determined to be in the full shade treatment. Therefore, the observed increase in total NH$_4^+$ and NO$_2^-$ + NO$_3^-$ is presumably due to an increase in leaf litter deposition, root and nodule turnover, and biological fixation by the full-growth *Erythrina* trees. Land use types have been determined to have a significant effect on NH$_4^+$ and NO$_2^-$ + NO$_3^-$ concentrations, as (Neill *et al.*, 1997) determined forested land use types have higher NH$_4^+$ and NO$_2^-$ + NO$_3^-$ concentrations in contrast to pasture lands. While a significant difference in NH$_4^+$ and NO$_2^-$ + NO$_3^-$ concentration by shade effect was calculated, no significant difference in net N mineralization rates were observed by fertilizer or shade treatments. No significant difference in net N mineralization rates by fertilizer and shade treatments indicates the presence of full-growth *Erythrina* contributes to higher concentrations of plant available N, without increasing the risk of rapid nitrification rates and increased N pollution.
In calculating the absolute quantification of the nitrifying bacteria group AOB by fertilizer and shade treatments, a significant difference in dsDNA copy number of AOB per soil g\(^{-1}\) was determined by shade effect. The highest concentration of dsDNA copy number of AOB per soil g\(^{-1}\) was observed in the full shade treatment. The AOB nitrifying community has been observed to have a greater biodiversity in rich organic carbon environments rather than in low organic carbon environments (Racz et al., 2010). Furthermore, the AOB community has been observed in high abundance in high NH\(_4^+\) environments (Huang et al., 2014). In this study, SOC was not significantly different between treatments; however, total SOC Mg ha\(^{-1}\) was high in each plot. Additionally, total NH\(_4^+\) concentration was significantly higher in the full shade treatment. The rich organic matter and higher NH\(_4^+\) environment of the full shade treatment may have contributed to a higher abundance of AOB when compared to the managed shade and no shade treatments.

In assessing the effects of inorganic fertilizer application on the transfer of biologically fixed N by *E. poeppigiana* to *Coffea arabica* in agroforestry systems, the hypothesis was that coffee plants closer to managed *Erythrina* would receive more N. Moreover, it was hypothesized that increased fertilizer application would negatively affect the biological N fixation in *E. poeppigiana*. The distance of coffee plants, up to 10 m, were not significantly different in mean \(\delta^{15}N\). These results are difficult to interpret. If the hypothesis was correct, the results would have shown a more linear relationship, with \(\delta^{15}N\) increasing with distance from the managed *Erythrina* tree. However, there is also a possibility that coffee plants in this study are receiving N from managed *Erythrina* up to a distance of 10 m in insignificantly different quantities. However, increased fertilizer
treatment had a significant effect on mean $\delta^{15}$N between treatments, the application of fertilizer may have negatively affected N fixing capacity.

This study could have been improved by adding more sampling periods before and after chemical fertilizer treatments. It would be interesting to better document the effects of chemical fertilizer treatments with respect to time. Having a better understanding of the pathways taken and volatilization time of chemical fertilizers in coffee agroforestry systems in Costa Rica would be beneficial in reducing N pollution. Furthermore, this study may have been improved with better field preservation methods for AOB sampling. Improved DNA preservation techniques from the field sampling to the isolation process may have resulted in better qPCR detection.
CHAPTER 5

CONCLUSIONS

Ultimately, intercropping with full-growth *E. poeppigiana* is a significant, ecologically based management practice to supplement the N pool in coffee agricultural systems. By intercropping with *E. poeppigiana* in coffee production systems, inorganic fertilizer applications can be reduced, bringing down the economic cost of production for the farmer and reducing the risk of N pollution through leaching and denitrification. Future research should target quantifying the least amount of inorganic fertilizer that can be applied to an *E. poeppigiana*-coffee agroforestry system without sacrifice to crop yield. Additionally, future studies should target the absolute quantification of AOA to determine which community, AOA or AOB, are more dominant in *E. poeppigiana*-coffee agroforestry systems. A better understanding of the nitrification process and net N mineralization rates could lead to improved deliverance of plant available forms of N in agricultural systems, while reducing the risk of negative environmental effects.
REFERENCES


Ingram, J.S.I., Gregory, P.J., Izac, A.M., 2008. The role of agronomic research in climate change and food security policy. Agriculture Ecosystems & Environment 126, 4-12.


Taugourdeau, S., le Maire, G., Avelino, J., Jones, J.R., Ramirez, L.G., Quesada, M.J.,
Charbonnier, F., Gomez-Delgado, F., Harmand, J.M., Rapidel, B., Vaast, P., Roupsard,
O., 2014. Leaf area index as an indicator of ecosystem services and management
practices: An application for coffee agroforestry. Agriculture Ecosystems & Environment
192, 19-37.


USDA., 1999. Soil taxonomy, a basic system of soil classification for making and
interpreting soil surveys. Natural Resources Conservation Service, Second Edition 329-
388.

PCR-denaturing gradient gel electrophoresis tool to study the diversity of Nitrobacter-like

Wood, S.L.R., Rhemtulla, J.M., Coomes, O.T., 2016. Intensification of tropical fallow-
based agriculture: Trading-off ecosystem services for economic gain in shifting
cultivation landscapes? Agriculture Ecosystems & Environment 215, 47-56.

Evolution 20, 553-560.