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Soil Nitrogen Dynamics in a Mixed-Species Tree Plantation and a Lowland Secondary Forest

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Abstract

Reforestation has been recognized as one of the strategies in climate change mitigation not only for its potential for carbon sequestration but also in restoring ecosystem functions and services. This study aimed to compare the rates of net nitrogen (N) mineralization and net nitrification in a mixed-species tree plantation and that of a secondary lowland forest. It also aimed to assess the potential of reforestation using the mixed-species strategy in restoring a key ecosystem function, particularly soil N cycling. The study was conducted within the Visayas State University campus in Baybay City, Leyte in two land uses, a lowland secondary forest and a mixed-species tree plantation established using the Rainforestation approach. No significant differences were found in extractable mineral N (NH_4^+ and NO_3^-) and net rates of N mineralization and nitrification between the mixed-species tree plantation and lowland secondary forest implying that N availability is similar for both the mixed-species tree plantation and the lowland secondary forest. Similar net rates of N mineralization and net nitrification for both sites suggest that they have the same rate of converting N to mineralized form which indicates that this mixed-species reforestation strategy may have potential to restore this ecosystem function, the soil N cycle. Further investigations are needed to evaluate the effects of species mixture and planting design on the soil N cycle as well as conducting similar studies on other sites under different conditions.

Keywords: soil nitrogen dynamics, net rate of nitrogen mineralization, net nitrification, mixed-species tree plantation, lowland tropical secondary forest

Introduction

Since tropical deforestation is a significant contributor of greenhouse gas emissions (GHGs) (Houghton, 2012), reforestation is considered one of the strategies in climate change mitigation mainly because of its potential for carbon sequestration (e.g., Locatelli *et al*., 2015; Mackey *et al*., 2013). Optimizing the benefits from reforestation requires filling in several knowledge gaps. For example, there is limited information on the ecosystem services produced by reforestation in the tropics (De Groot & Van der Meer, 2010). Reforestation can restore biogeochemical cycling of carbon, oxygen, and nutrients (Arneth *et al*., 2010) and can increase resilience to pressures from climate change (Hooper *et al*., 2005). How ecosystem functions such as the soil nitrogen (N) cycling response to reforestation is of interest because this ecosystem function plays a role in regulating the sequestration and release of GHGs like N2O and NO (e.g., Baldos, 2014) and is a strong forcing factor for global climate change (Hall & Matson, 2003).

Reforestation changes nutrient cycling due to changes in quantity and quality of inputs and rates of uptake. Decomposition of litter and, therefore, the cycling of nutrients is slower after reforestation because of the lignified nature of litter from trees and the shift toward a fungal-dominated assemblage in the soil (MacDonald *et al*., 2009). The tree species used in planting affects the breakdown of litter due to differences in quality (e.g., deciduous vs. evergreen species, Cornwell *et al*., 2008). However, environmental differences

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among plantings (e.g., soil moisture and stream temperatures) may have larger effects on litter decomposition than the species mix of litter (Lacan *et al.*, 2010). Changes in soil N after reforestation may depend on site productivity, with losses in high rainfall areas (>1200 mm year^{-1}) but gains in low rainfall sites (<800 mm year^{-1}, Berthrong *et al.*, 2012) and on degraded soils (Jiao *et al.*, 2012). Mixed-species reforestation increased N mineralization indicating its potential as a sustainable approach to restoring degraded lands (Mo *et al.*, 2016) and may potentially alleviate N losses associated with nitrification and denitrification and favor N retention (Reverchon *et al.*, 2015).

The objective of this study was to characterize and compare the soil N dynamics in terms of indices of nitrogen cycling, namely the rates of net N mineralization and net nitrification in a mixed-species tree plantation and that of a secondary lowland forest. Results from this study could serve as one of the bases to assess the potential of reforestation in restoring a key ecosystem function, namely soil N cycling and in turn in mitigating the impacts of climate change.

Materials and Methods

Study Area

The study sites were inside the Visayas State University campus in Baybay City, Leyte, Philippines (9^{o}55' to 11^{o}48'N and 124^{o}17' to 125^{o}18' E). The researchers conducted their study in two land uses, a secondary lowland forest and a mixed-species tree plantation. The mixed-species tree plantation established in 1993 using the Rainforestation approach and growing on Acrisol soil developed from volcanic parent material (Navarette *et al.*, 2009), was composed of fast-growing pioneer trees (e.g., Trema orientalis, Artocarpus sericicarpus) planted at close interval with shade-obligate trees, most of which were high value timber species of the family Dipterocarpaceae (Milan *et al.*, 1994; Milan *et al.*, 2004), with a stand density of 66.11 expressed as number of trees per plot (Milan *et al.*, 2004). The secondary forest site was composed mainly of species belonging to the Moraceae family growing on Acrisol and Nitisol soils developed from volcanic parent material (Asio, 1996; Navarrete *et al.*, 2009). Acrisols and Nitisols contain low activity clays, with the former exhibiting low base status while the latter, P fixation. Both often support forested areas [International Union of Soil Sciences (IUSS) World Reference Base (WRB), 2015]. Both sites have a thin litter layer (<5 cm thick) but no organic layer. The above-mentioned sites were within 1 km distance from each other and were approximately 50 meters above sea level in elevation. Leyte Province has a humid monsoon climate (Kolb, 2003) and the average rainfall in the study area for the years 1976–2008 was 2,828 mm. The average annual temperature was 27.5^{o}C and the relative humidity was always high with an average monthly level for the years 1980–2000 ranging from 75.1% to 80.1% (Kolb, 2003). Ambient nutrient deposition near the sites was not measured.

Soil Sampling Design, Collection, and Preparation

In each site (mixed-species tree plantation and lowland secondary forest), 5 sampling points were marked at 10-meter (m) intervals along a 50-meter transect. Processes that were mediated by microorganisms such as N cycling were reported to show spatial independence at similar or even shorter distance: 0.10-meter distance for N_2O emission (Ambus & Christensen, 1994) and 10-meter distance for gross rates of microbial N cycle (Corre *et al.*, 2002) hence the use of 10-meter intervals between the sampling points since the researchers were investigating rates of N cycling.

Soil at a depth of 0–5 cm were sampled from each of the 5 replicate sampling points along the 50-meter transect established in the mixed-species tree plantation and the lowland secondary forest. Soil samples were air-dried, ground, and analyzed for total C and N using a CN analyzer (Elementar Vario EL; Elementar Analysis Systems GmbH, Hanau, Germany). Soil pH was measured from a mixture of soil and distilled water with a ratio of 1:4 (e.g., Baldos *et al.*, 2014). All soil samples were analyzed at the laboratory of Soil Science of Tropical and Subtropical Ecosystems (SSTSE), University of Goettingen, Germany.

Soil Nitrogen Cycling

Sampling was done in November 2008, and the buried bag method was used to measure net rates of N cycling (Hart *et al.*, 1994). The focus of this study was mainly to describe the dynamics of soil N approximately 15 years from establishment of the mixed - species tree plantation. At each sampling point, 2 intact soil cores (8-cm diameter and 5-cm depth) were taken from the top 5-cm depth of the soil.

One subsample was extracted immediately in the field with 150 mL of 0.5 M K_2SO_4 to determine the initial NH_4^+ and NO_3^- levels (T_0). Another plastic bag containing the other subsample was buried in the soil for 7 days and was extracted with 0.5 M K_2SO_4 (T_1) afterward. The plastic bag was closed with a rubber band to prevent rain coming in but not too tight to permit air exchange. Mineral N extraction was completed at the laboratory of the College of Forestry and Environmental Science, Visayas State University on the same day of sampling by shaking the soil-K_2SO_4 bottles for 1 hour and filtering them through K_2SO_4-prewashed filter papers. The extracts were frozen immediately and were kept frozen during air transport to the Soil Science of Sub-Tropical and Tropical Ecosystems Laboratory (SSTSE), University of Goettingen, Germany where NH_4^+, and NO_3^- were analyzed using continuous flow injection colorimetry (CENCO/Skalar Instruments, Breda, Netherlands). Net rates of N mineralization and net nitrification were calculated by subtracting the sum of the initial NH_4^+ and NO_3^- concentrations (T_0) from those after incubation (T_1) and divided by the days of incubation (7 days). From each soil core, gravimetric water content and bulk density were also determined by taking a subsample and oven-drying them at 105^{o}C for 24 hours.

Data Analysis

Descriptive analysis was used to determine the mean, standard error of the parameters measured in the study. Tests for normality using Kolmogorov-Smirnov D statistic and for equality of variance using Levene statistic (Sokal & Rohlf, 1981) were first conducted for each parameter. Parameters that showed heterogeneous variance were log-transformed. Independent t-test was used to determine if the net rates of N cycling in the mixed-species tree plantation were different with the estimated values for the lowland secondary forest. The levels of significance were set at $P \leq 0.05$. All statistical analyses were conducted using R.

Results and Discussion

No significant differences were found in the measured soil characteristics between the mixed-species tree plantation and the lowland secondary forest at 0-5 cm depth (Table 1). There were no significant differences in extractable mineral N (NH_4^+ and NO_3^-) ($P = 0.228$, and $P = 0.174$, respectively [Table 1]) and in net rates of N mineralization and nitrification ($P = 0.11$, and $P = 0.27$, respectively [Table 1]) between the mixed-species tree plantation and lowland secondary forest.

Similarity, the extractable mineral N concentrations imply that N availability is similar for both the mixed-species tree plantation and the lowland secondary forest while similar rates of net N mineralization and net nitrification for both sites suggests that

Table 1: *Soil characteristics (mean ± SE, n = 5) of the mixed-species tree plantation and lowland secondary forest*

	Mixed-species Tree Plantation (Rainforestation)	Lowland Secondary Forest
Water-filled pore space (WFPS), %	56.45 (7.37)^{A}	59.89 (6.83)^{A}
Bulk density, g cm^{-3}	1.02 (0.14)^{A}	1.09 (0.11)^{A}
Organic carbon, %	2.46 (0.65)^{A}	2.12 (0.83)^{A}
Total nitrogen, %	0.24 (0.05)^{A}	0.22 (0.02)^{A}
C:N	9.71 (0.92)^{A}	9.64 (0.90)^{A}

^{A} *Means with different capital letters indicate significant differences between sites (Paired t-test at $P \leq 0.05$).*

Table 2: *Mean (±SE, N=5) extractable mineral nitrogen (NH_4^+ and NO_3^-) and net rates of soil N cycling (net N mineralization and net nitrification) in a mixed-species tree plantation and a lowland secondary forest*

Site	Extractable Mineral Nitrogen		Net Rates of N Cycling	
	NH_4^+ (μg N cm^{-2})	NO_3^- (μg N cm^{-2})	Net N Mineralization (μg N g^{-1} d^{-1})	Net Nitrification (μg N g^{-1} d^{-1})
Mixed-species tree plantation (Rainforestation)	44.63 (0.43)^{A}	9.15 (2.03)^{A}	0.60 (0.11)^{A}	0.03 (0.02)^{A}
Lowland secondary forest	43.51(0.31)^{A}	7.84 (1.45)^{A}	0.70 (0.09)^{A}	0.02 (0.01)^{A}

^{A} *Means with similar capital letters indicate significant differences between sites (Paired t-test at $P \leq 0.05$).*

both sites have the same rate of converting N to mineralized form. The methods used in this study is only limited to the description of the status of the soil N dynamics; hence, it is quite difficult to establish whether this non-significance of results might be due to the effect of the original vegetation, although, this similarity could be partly explained by the similarity in the climatic conditions of the sites (Navarette *et al.*, 2010).

Favorable soil physical conditions in both the mixed-species tree plantation and the lowland secondary forest could also explain this non-significant difference between the 2 sites. This may suggest that establishment of the mixed-species tree plantation may have aided in recovering from the soil degradation processes that have occurred in the area long before it was reforested. First, the soil water status, expressed as percent (%) water-filled pore space (%WFPS), ranged from 50% to 60% in both of the sites (Table 1), which fell within the range of %WFPS (60% WFPS, field capacity) that is considered optimal for microbial activity (Linn & Doran, 1984). Field capacity is reckoned to be the shifting point in water content wherein both oxidative and reductive processes are active in the soil (Davidson *et al.*, 2000). At this point, micropores are filled with water, allowing microbial activity without water stress, and macropores are filled with air, leading to relatively good aeration of the bulk of the soil, although anaerobic microsites may exist.

Second, soil bulk densities for both sites were at 1.00 g cm^{-3} (Table 1), which may have facilitated soil microorganism activity and influenced key soil processes such as decomposition and mineralization (Cresswell & Hamilton, 2002; McKenzie *et al.*, 2004). Generally, a soil with a bulk density value of less than 1.50 g cm^{-3} facilitates optimum movement of air and water through the soil (Hunt & Gilkes, 1992).

Third, the low C:N ratios of both sites (Table 1), similar to soil C:N ratios measured under secondary forest and the same mixed-species tree plantation (Navarette & Tsutsuki, 2008), were favorable for decomposition, and hence, net N mineralization. Soil C:N ratios not only reflect the stoichiometric demand of soil microorganisms but also the influence of substrate quality (Baldos *et al.*, 2015) and is one indication that soil biochemical conditions in both sites were favorable for the production of mineral N in these sites.

Net nitrification rates for both sites were positive indicating a net accumulation of NO_3^-(Table 2). As the difference between T_1 and T_0 NO_3^- concentration divided by number of days buried in soil basically means that plant N uptake was excluded during the 7-day incubation period, the detectable net nitrification rates (Table 2) suggests that nitrifiers could compete for available N during this period of plant-uptake exclusion. In addition, the NO_3^- produced was not all consumed through microbial immobilization so as to be detectable. This implies that mineral N production was larger than its consumption, depicting a less competitive condition for available N. This suggests that if this NO_3^- does not get consumed by microbes or taken up by plants, this accumulation has the potential to be lost from the system either as gaseous emissions or via leaching.

Conclusion

Our results show no significant differences in rates of net mineralization and nitrification between mixed-species tree plantation and lowland secondary forest. This suggests that a mixed-specie s reforestation strategy may have the potential to mimic a lowland secondary forest in terms of its N supplying capacity implying that this strategy may be able to restore a key ecosystem function such as the soil N cycle. Further investigations are needed to evaluate the effects of species mixture and planting design on the soil N cycle as well as conducting similar studies on other sites under different conditions.

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