TROPICAL TREE PLANTATION ROTATION EFFECTS ON FERTILITY, EARTHWORM ABUNDANCE, AND BIOMASS OF A HYDRUDAND SOIL IN HAWAI‘I

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This study examined how second-rotation tree species affected: (1) soil fertility and soil organic C for the 0- to 15- and 15- to 30-cm depths of an Akaka silty clay loam (Acrudoxic Hydudand) three and six years into the second rotation that followed an 18-year first rotation and, (2) earthworm abundance, and biomass. Four first-second rotation species pairings were used: Sydney blue gum [SBG, *Eucalyptus saligna*)] to SBG, albizia [ALB, *Falcataria moluccana*)] to ALB, SBG to ALB and ALB to SBG. Rotation affected soil pH at the 0- to 15-cm depth and were primarily attributed to the legacy effects with lower pH for rotations first planted to ALB than SBG. The SBG→ALB rotation consistently had greater exchangeable Ca and Mg than the other rotations at both soil depths. By year six there was: (1) greater soil organic C concentration and organic C gain since the first rotation at the 0- to 15-cm depth for ALB→ALB than SBG→SBG but ALB→ALB did not differ from SBG→ALB or ALB→SBG, (2) soil total N buildup from N₂-fixation by ALB in SBG→ALB and total N decline for SBG→SBG, and (3) no difference in soil total N difference between ALB→SBG and SBG→ALB or between ALB→ALB and SBG→ALB. We found that both *Amynthas gracilis* and *Pontoscolex corethrurus* earthworms had greater densities and biomass in the treatment ALB→ALB than in the other treatments and were both positively correlated with soil N.
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CHAPTER 1: INTRODUCTION

Forest plantation rotation effects on soil fertility are currently understudied. According to Evans (2001) few have examined the soil chemistry changes over successive rotations as most large-scale plantations are monocultures. Of the data collected on successive rotations most are unreliable because data are rarely maintained from one rotation to the next and focus primarily on yield rather than soil (Evans, 2001).

Forest plantation is a forest stand established by planting/seeding for the purpose of afforestation or reforestation (FAO, 2000). This type of plantation usually consists of a single species with uniform planting densities and even age class that are either introduced or indigenous species. These plantations typically have a minimum area of 0.5 ha, 10 percent of the land cover consists of tree crown cover and the total height of mature trees are above 5 m. As of 2000, there were 187 million hectares of forest plantations reported (FAO, 2000). Forest plantations are mainly used as a source of fiber in the wood industry.

Short-rotation forestry is a type of forest plantation that uses silvicultural practices to produce high-density plantations of fast-growing tree species to produce woody biomass for construction, pulp, paper, fodder and energy on fertile yet degraded forest lands or agricultural lands (Christersson and Verma). Rotation periods usually are under 15 years. *Eucalyptus* and *Acacia* are the main genera used in short-rotation forestry worldwide (FAO, 2000).

In the Hawaii, short-rotation forestry was initiated for biomass for fuel production (DeBell et al., 1987; Whitesell, 1992). Eucalyptus plantations were successfully grown on most sites selected on the Big Island, however, additions of nitrogen (N) were needed to sustain growth and high yields (Schubert and Whitesell, 1985). These inputs can be expensive in dollars
Nitrogen-fixing trees such as *Falcataria moluccana* (Miquel) Barneby & J.W. Grimes] also known as albizia can provide N needed by Eucalyptus to maintain high yields. Long-term productivity of tropical plantations depends on continued supplies of nutrients and these supplies may be strongly influenced by the species selected for plantation use (Binkley, 1997).

Productivity of short-rotation forest plantations is strongly dependent on soil fertility. Soil fertility, is defined as the “status of the soil with respect to its ability to supply elements essential for plant growth without a toxic concentration of any element” (Foth and Ellis, 1997). Soil fertility can be dependent on soil formation factors which include parent material, climate (i.e., precipitation, temperature), biota, time and topography (Mahilum, 2004) and also tree species (Binkley and Giardina, 1998).

The following projects were initiated to investigate the effects that planting a different tree species versus the same species during the second rotation on a tropical tree plantation on the soil fertility of Akaka silty clay loam (Hydrudand) in Hawaii. The study further investigates: 1) how long soil N enrichment in the first rotation by the N-fixing species will last into the second rotation of the non-N-fixing species, and 2) if N enrichment will increase if an N-fixing species is again used during the second rotation. The study also aims to determine the effects of rotation on the abundance and biomass of earthworm populations.
CHAPTER 2: SECOND-ROTATION TROPICAL TREE PLANTATION EFFECTS ON FERTILITY OF A HYDRUDAND SOIL

2.1 INTRODUCTION

On the Island of Hawai‘i, sugarcane (*Saccharum* spp.) plantation agriculture slowly declined over a 30-yr period until operations ceased in 1996. Many of these former sugarcane lands were converted to plantations of fast-growing trees. Like other crops the productivity of forest plantations depends strongly on soil fertility, and the supply of nutrients in the surface soil can change substantially under the influence of different tree species (Sanchez et al., 1985; Hartemink, 2003; Russell et al., 2007). For example, N-fixing species can greatly enhance the soil N supply (Garcia-Montiel and Binkley, 1998; Mathews et al., 2002).

In a 18-yr Hawai‘i study on an Akaka silty clay loam (Acrudoxic Hydrudand) formerly cropped to sugarcane, Mathews et al. (2002) observed a differential soil N accumulation of ~1200 kg N ha⁻¹ to a 30-cm depth for first-rotation N-fixing albizia [ALB, *Falcataria moluccana* (Miquel) Barneby & J.W. Grimes] in comparison with first-rotation Sydney blue gum [SBG, *Eucalyptus saligna* (Sm.)] and a naturalized fallow of hilograss (*Paspalum conjugatum* Bergius). Differences in soil exchangeable cations, extractable P fractions, and organic C among species were few and of relatively small magnitude but ALB decreased soil pH by 0.2 units. This result for pH was most likely due to acidity generated from the nitrification of mineralized N. Pronounced tree species effects on exchangeable cations are more likely to occur on fertile soils than on acidic, nutrient poor soils like the Akaka series (Kang and Akinnifesi, 1994).

Review of the literature indicated that replicated studies examining legacy effects of first-rotation tree species on soil fertility and soil organic C in the second rotation have apparently not

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been previously conducted in the tropics. Determining how long first-rotation soil N enrichment by N-fixing species will last into the following rotation of a non N-fixing species, and whether N enrichment will be even greater if an N-fixing species is again used for the second rotation are important issues for sustainable forest plantation management (Weston, 2001).

The objectives of this study were to determine: (1) if keeping the same or switching to a different tree species for the second rotation affects soil acidity, cation exchange properties, concentrations of total C and N, extractable inorganic N, and net N mineralization for the 0- to 15- and 15- to 30-cm depths of an Akaka silty clay loam following an 18-yr first rotation, and (2) if these properties change during the course of the second rotation.

2.2 METHODS

Site Description

The study was conducted at two adjacent sites, locally known as Kamae, located at 480 m elevation above Hakalau town on the northeast coast of the Island of Hawaiʻi (19°52′ N, 155° 9′ W). The mean annual precipitation is 4600 mm, and the mean annual temperature is 21°C. One of the sites is in a well-drained, mid-slope position while the other site is in a wetter, lower slope position with a gravelly subsoil (partially weathered cinders and a'a clinkers) at a depth of 30 to 60 cm (Mathews et al., 2002). The lower, more poorly drained site has greater concentrations of exchangeable Ca and Mg, perhaps due in part to decreased leaching potential and some Ca and Mg release from the partially weathered materials (Mathews et al., 2002). It is also slightly lower in soil organic C than the upper site. The soil at both sites is an Akaka silty clay loam (hydrous, ferrihydritic, isothermic Acrudoxic Hydrudands) derived from weathered volcanic ash and cinders (Hue et al., 2007). Akaka soils have moderate slopes (<15%) and are usually
moderately well-drained with slow runoff and high permeability. Ferrihydrite, allophone-imogolite, and goethite are the dominant minerals in Akaka soil along with ~10% micas/illite and 5% each of gibbsite and feldspars (Soil Survey Staff, 1976; Parfitt et al., 1988). Soil bulk density determined by the core method averages 0.48 and 0.45 Mg m$^3$ at depths of 0 to 15, and 15 to 30 cm, respectively, with no apparent effect of species (Mathews et al., 2002). These very low bulk density values are within the expected range of 0.3 to 0.6 Mg m$^3$ for the Akaka soil and other Hydrudands (Soil Survey Staff, 1976; Parfitt et al., 1988).

Prior to establishing the first rotation in 1982 both sites had been under continuous sugarcane (interspecific hybrids of *Saccharum* spp.) cultivation for 50 years. The first rotation consisted of replicate monoculture plots of SBG (n=4) and ALB (n=4) at each site. The trees were planted at a spacing of 1.5 x 1.5 m in 12 x 18 m plots arranged in a randomized design at each site. All plots received a total of 110 kg N ha$^{-1}$ as NH$_4$NO$_3$, 50 kg P ha$^{-1}$ as Ca(H$_2$PO$_4$)$_2$, and 90 kg K ha$^{-1}$ as KCl at the time of planting. Some thimbleberry (*Rubus rosifolius* Sm.) was present in all plots. For further site details the reader is referred to Mathews et al. (2002).

First-rotation trees from each site were subjected to an aboveground only, whole-tree harvest. The trees were felled by hand and logs along with slash residue were mechanically removed using a Timberjack 735 shovel logger. All tree biomass was removed by working from the exterior of the plots in order to minimize soil disturbance by machinery and thus preserve first-rotation species effects on soil fertility. Glyphosate herbicide (containing 2.0% active ingredient, *N*-phosphonomethylglycine) was applied (9.4 L ha$^{-1}$) to remaining undergrowth and tree stumps.
Second Rotation Experimental Design

Approximately one year after the first rotation was harvested, one half the plots at each site were randomly selected for replanting with the same species used in the first rotation. The remaining plots at each site were designated for replanting with the alternate species. Tree spacing was kept at 1.5 x 1.5 m. This resulted in two replicates per site for each of the four possible rotations: SBG→SBG, ALB→ALB, SBG→ALB, and ALB→SBG. Thus, the experimental design is a generalized randomized block design (GRBD) consisting of four rotations replicated twice at each of two sites.

Soil Sampling and Analysis

Soil sampling occurred a year prior to harvesting the first-rotation trees (Table 2.1; Mathews et al., 2002) and years three (May 2004) and six (May 2007) after replanting with the second rotation. Samples were obtained from 15 cores collected around the center of each plot to avoid effects from the neighboring tree species (Mathews et al., 2002). A 2.5-cm diam. corer was used to collect samples at depths of 0 to 15 cm (Ap horizon) and 15 to 30 cm (Bw1 horizon). Before coring, the litter layer was pushed aside. The 15 core samples per plot per depth were composited into plastic bags, placed in an ice cooler, transported to the laboratory where they were immediately sieved through a 1-cm screen to remove roots and worms, and refrigerated at 4°C prior to complete analysis within a few days.

Soil pH was measured by glass electrode in deionized water at a fresh soil-to-solution ratio of 1:1. Exchangeable cations were extracted from field-moist soil (2.5 g dry-soil equivalent) by shaking for 30 min with 50 mL of 0.2 M NH₄Cl followed by filtration through Whatman No. 42 filter paper (Mathews et al., 2002). Concentrations of Ca, Mg, K, and Al were measured by Inductively Coupled Plasma Emission Spectroscopy (Hue et al., 2000).
Total soil N was determined by a micro-Kjedahl method using 0.2 g oven-dry soil while available inorganic N (NH₄-N + NO₃-N) was extracted from field moist soil (10.0 g dry-soil equivalent) by shaking for 1 hr with 100 mL of 1 M KCl (Hue et al., 2000; Maynard et al., 2008). All N analyses were performed colorimetrically (Maynard et al., 2008). Readily mineralizable N (RMN) was determined by the anaerobic incubation procedure outlined by Sahrawat and Narteh (2003). Soil organic C was determined by a chromic acid colorimetric procedure (Hue et al., 2000). Soil bulk density was used to convert organic C and total N concentration differences among rotations to a Mg per ha gain or loss basis since the first rotation (Mathews et al., 2002).

Modified-Truog (0.01 M H₂SO₄ + 0.02 M [NH₄]₂SO₄) extractable P, the standard agronomic P test for acid soils in Hawai‘i, was determined by the colorimetric (molybdenum blue) procedure outlined by Hue et al. (2000). Soil inorganic and total P were determined by the 0.5 M H₂SO₄ extraction procedure outlined by O’Halloran and Cade-Menum (2008) using non-ignited and ignited (540°C) samples, followed by colorimetric analysis.

Statistical Analyses

Data were analyzed by PROC GLM of the Statistical Analysis System (SAS Institute, 2003) using the appropriate models for a GRBD (Hinkelmann and Kempthorne, 1994). Rotation, site, and year were considered as fixed effects (Piepho et al., 2003). Year was considered a fixed sub-plot effect because of the cumulative effects of rotations in studies involving perennial crops where year effects can carry over into subsequent years. For further comparison of the first- and second-rotation species effects the data were also analyzed as a function of the first- and second-rotation species and their interactions arranged in a GRBD. All main effects and their interactions were considered significant at $P \leq 0.10$. Rotation means were separated using Fisher’s F-protected LSD test at $P = 0.05$ or $P = 0.10$ depending if the overall F-
test for rotation was significant at \( P \leq 0.05 \), or \( > 0.05 \) but \( \leq 0.10 \) (Gomez and Gomez, 1984). The level of significance for the LSD test is noted.

2.3 RESULTS AND DISCUSSION

Rotation Effects on Soil pH, Concentrations of Exchangeable Cations, Effective Cation Exchange Capacity, and Aluminum Saturation

0- to 15-cm Depth

Rotation affected pH \( (P < 0.10) \), exchangeable Ca and Mg \( (P < 0.05) \), Al saturation \( (P < 0.05) \), and ECEC \( (P < 0.10) \) in both years at the 0- to 15-cm soil depth (Table 2.2). Rotation effects for exchangeable K were only observed \( (P < 0.05) \) in year 6. Year effects were observed for pH \( (P = 0.07) \), exchangeable Ca, Mg, and K \( (P < 0.03) \), Al saturation \( (P = 0.003) \), and ECEC \( (P = 0.10) \). Rotation x site interactions were not significant \( (P > 0.22) \). Rotation x year interactions were observed for pH \( (P = 0.10) \) and exchangeable Ca \( (P = 0.01) \), however, the interaction for Ca was due to magnitude of response rather than direction of response.

Soil pH was greater for the SBG→ALB rotation than ALB→ALB and ALB→SBG in year 3, but did not differ from SBG→SBG (Table 2.2). In year 6, a similar pattern was observed but SBG-ALB only differed from ALB→ALB. Statistical analysis as a function of the first- and second-rotation species revealed that the results for pH were primarily first-rotation species effects \( (P < 0.02) \) as there were no second-rotation species effects \( (P > 0.48) \) on pH. It is well known that in the long-term ALB increases soil acidity and SBG also acidifies soil but at a slower rate than ALB (Mathews et al., 2002). This is because in addition to soil base cation uptake and retention, ALB generates considerable acidity via mineralized soil N inputs which undergo the \( H^+ \) generating nitrification process (Mathews et al., 2002). Eucalyptus species such
as SBG acidify the soil primarily by base cation retention in woody biomass coupled with leaf litter of low ash alkalinity (Noble et al., 1996; Weston, 2001). The lack of a second-rotation species effect on pH may suggest that six years is too short for ALB to acidify former SBG plots or may indicate inputs of mixed litters, exudates, and leachates can have an effect counter to the expected acidification by ALB. It is interesting to note that at initiation of the second rotation the first-rotation SBG plots had a pH of 4.6 for the 0- to 15-cm soil depth (Table 2.1) and although not significant \((P > 0.10)\), the pH in this layer six years later was 4.8 for SBG→ALB compared to a constant 4.6 for SBG→SBG (Table 2.2). After 5 yr, DeBell et al. (1985) noticed a similar trend on an Akaka soil where SBG and ALB simultaneously planted together in alternate rows in order to provide plots with a 1:1 mixture had a soil pH of 5.4 compared to a pH of 5.2 for pure SBG plots. The greater overall pH values in their study were likely due to the residual effects of lime \((\approx 2000 \text{ kg ha}^{-1})\) applied to the last sugarcane crop.

In both years, exchangeable Ca and Mg were greater for SBG→ALB than the other rotations (Table 2.2). A somewhat similar pattern occurred for exchangeable K in year 6 except that ALB-ALB also had a greater K concentration than SBG-SBG. Senock (2003, unpublished data, California State Univ., Chico) found that ALB in SBG→ALB had greater leaf tissue K concentrations than the other rotations \((7.4 \text{ g kg}^{-1} \text{ vs } 6.1 \pm 0.5 \text{ g kg}^{-1})\). The factors contributing to greater exchangeable base cations with SBG→ALB are difficult to explain but may be due in part to the young ALB trees serving as a source of N and readily decomposed organic matter to accelerate microbial turnover of more recalcitrant SBG-derived organic matter from the first rotation (Briones and Ineson, 1996; Forrester et al., 2006). DeBell et al. (1985) found that surface soil exchangeable Ca and Mg concentrations were greater in their mixed plantings of SBG and ALB than in pure SBG. The overall decreases in exchangeable Ca and Mg since
initiation of the second rotation for all rotations except SBG→ALB (Table 2.1 vs Table 2.2) are probably associated with both leaching and tree uptake. From an agronomic soil fertility standpoint the rotation effects on exchangeable Ca, Mg, and K were of small magnitude (Yost and Uchida, 2000) and do not indicate that ALB and SBG will induce pronounced changes in the base cation fertility status of nutrient poor soils like the Akaka series.

Considerable rotation variation existed for exchangeable Al but there were no significant differences in either year ($P > 0.21$). The high variation in exchangeable Al may have been due in part to the relative proximity of the soil samples to decomposing tree trunks and roots from the first rotation (Baba and Okazaki, 2000). These materials can increase exchangeable Al concentrations via organic acid induced Al mobilization from allophone in Andisols (Baba and Okazaki, 2000). In year 3, ECEC was greater for SBG→ALB than SBG→SBG and ALB→SBG but did not differ from ALB→ALB. In year 6, a similar pattern occurred except ECEC for SBG→ALB was greater than all other rotations. This response can be attributed to the greater concentrations of exchangeable Ca and Mg with SBG→ALB which also contributed to a lower Al saturation of the ECEC for this rotation. Over time as ALB acidifies the soil in the SBG→ALB rotation, the base cations and ECEC are likely to decline while exchangeable Al, Al saturation, and solution Al will increase (Baba and Okazaki, 2000; Mathews et al., 2002). This is because the nitrification that occurs as N accumulates in the soil leads to a decrease in pH; concomitantly base cations are leached due a decline in ECEC.

15- to 30-cm Depth

There were rotation effects for exchangeable Ca and Mg ($P < 0.05$) in both years, while Al saturation ($P < 0.10$) differed among rotations only in year 6 ($P = 0.03$ for rotation x year interaction) (Table 2.3). Year effects occurred for pH ($P = 0.002$), exchangeable Ca, Mg, K, and
Al, and ECEC ($P < 0.03$). Rotation x site interactions were not significant ($P > 0.13$). There were no significant pH differences among rotations in either year 3 (mean = 4.9) or year 6 (mean = 4.7) (Table 2.3). Similar to the results for the 0- to 15- cm depth, SBG→ALB had or tended to have greater exchangeable Ca and Mg than the other rotations in both years. Also like the results found at the 0- to 15-cm depth, there was considerable variation for exchangeable Al, but no significant rotation effects ($P > 0.30$). There were no differences in ECEC in either year ($P > 0.25$). In year 3, there were no differences ($P > 0.18$) for Al saturation, however in year 6, SBG→SBG, ALB→ALB, and ALB→SBG had greater ($P < 0.10$) percentages than SBG→ALB.

Rotation Effects on Total Soil Organic C, Total N, C:N Ratio, 1M KCl Extractable NH$_4$-N and NO$_3$-N and RMN

0- to 15-cm Depth

There were rotation effects for total N, C:N ratio and RMN ($P < 0.05$) for both years whereas, there were rotation effects ($P < 0.10$) for soil organic C, organic C gain since the first rotation, total N gain/loss since the first rotation, and NO$_3$-N ($P < 0.05$) in year 6 only (Table 2.4). There were year effects for total N ($P = 0.004$), total N gain/loss ($P = 0.003$), C:N ratio ($P = 0.0004$), NH$_4$-N ($P = 0.08$), NO$_3$-N ($P = 0.001$) and RMN ($P = 0.01$). Rotation x site interactions were not significant ($P > 0.14$) but there were rotation x year interactions for total N ($P = 0.05$), C:N ratio ($P = 0.02$) and NO$_3$-N ($P = 0.08$).

In year 6, greater soil organic C concentration and organic C gain since the first rotation were observed for ALB→ALB than SBG→SBG but ALB→ALB did not differ from SBG→ALB or ALB→SBG. While N additions from legumes such as ALB often stimulate fresh litter decomposition rates by microbes they may also serve to enhance soil organic C because N
is a substrate for humification and mineral N can suppress the ligninolytic enzymes of humus degrading soil microbes (Fog, 1998; Resh et al., 2002; Moran et al., 2005; Jandl et al., 2007). However, stabilization as amorphous Fe- and Al-oxide and clay mineral aggregates and surface complexes is the primary reason why humus has a low turnover rate and there is a limit to their ability to provide physical and chemical protection from decomposition (Six et al., 2002; Jandl et al., 2007). Thus, soils can become saturated with humus and not stabilize any more even when inputs of organic C increase (Six et al., 2002; Jandl et al., 2007). The effects of N additions on the stability and turnover of soil carbon are indeed complicated because the information available is conflicting on whether excessive N availability exacerbates soil organic C loss in the long-term (Khan et al., 2007; Coulter et al., 2009).

Soil total N was greater ($P < 0.05$) in ALB→ALB and ALB→SBG than the other rotations in year 3. Statistical analysis as a function of the first- and second-rotation species revealed that this response was a first-rotation species legacy effect ($P < 0.002$) as there were no second-rotation species effect ($P > 0.47$) on soil total N in year 3. By year 6, ALB→ALB still had the greatest total N concentration but no longer significantly differed from SBG→ALB. This response was due to the emergence of a second-rotation species effect ($P < 0.001$) in year 6 in addition to a first-rotation species legacy effect ($P < 0.01$). Furthermore, ALB→SBG had a greater total N concentration than SBG→SBG. These results reflect N buildup from N$_2$-fixation by ALB in SBG→ALB while total N declined or tended to decline in SBG→SBG and ALB→SBG. The data also suggest that soil N accumulation may have reached the saturation point for ALB→ALB as the mean total N for year 6 was slightly smaller than observed in year 3. Accumulation of N in ALB→ALB soil may have been reduced by tree N uptake from the high existing first-rotation soil N supply coupled with a lower N-fixation rate in the second rotation.
induced by the high soil N status (Binkley and Giardina, 1997; Pastor and Binkley, 1998). Like organic C, the capacity of soils to stabilize additional N is also dependent on the amounts already in the soil rather than the level of input (Six et al., 2002). In year 3, SBG→SBG and SBG→ALB had wider C:N ratios compared to the other rotations. Statistical analysis as a function of the first- and second-rotation species revealed that this response for C:N ratio was a first-rotation species legacy effect \( (P < 0.001) \) as there was no second-rotation species effect \( (P > 0.41) \) on C:N ratio in year 3. In year 6, SBG→SBG had a wider C:N ratio than the other rotations which did not differ amongst each other. This result occurred because of the total N buildup in SBG→ALB and N loss from ALB→SBG indicating the emergence of a second-rotation species effect \( (P < 0.02) \) on C:N ratio in addition to a first-rotation species legacy effect \( (P < 0.05) \).

In both years there were no significant differences for NH4-N \( (P > 0.11) \). In year 3, there were no significant rotation effects for NO3-N \( (P > 0.14) \) however, in year 6 ALB→ALB had a greater concentration than SBG→SBG and ALB→SBG but did not differ from SBG→ALB (Table 2.4). In both years, RMN was greater for ALB→ALB and ALB→SBG than the other rotations with the exception that they did not differ from SBG→ALB in year 6. Overall the levels of RMN in the present study are rather high and likely reflect the high concentrations of organic C present in the Akaka soil (Mathews et al., 2002).

**15- to 30-cm Depth**

Rotation x site interactions were not significant \( (P > 0.14) \) but there were rotation x year interactions for soil organic C \( (P = 0.002) \) and total N \( (P = 0.07) \). In year 3, there were rotation effects for soil organic C \( (P < 0.10) \) and OC gain since the first rotation \( (P < 0.05) \) (Table 2.5). In year 6 there were rotation effects for total N and total N gain since the first rotation \( (P < 0.10) \) but there were no rotation effects in either year for C:N ratio, NH4-N, NO3-N, and RMN.
Similar to the results found at the 0- to 15-cm depth, there were year effects for total N ($P < 0.01$), C:N ratio ($P < 0.0001$), NH$_4$-N ($P < 0.001$), NO$_3$-N ($P < 0.01$), and RMN ($P < 0.07$).

In year 3, the total soil organic C in SBG→ALB was greater than the other rotations with similar trends for organic C gain since the first rotation (Table 2.5). In year 6 ALB→SBG had a greater total N concentration than SBG→SBG and SBG→ALB but did not differ from ALB→ALB (Table 2.5).

Rotation Effects on Modified-Truog Extractable P, Inorganic P and Total P

There were no tree species or rotation effects on soil P. There were no differences ($P > 0.19$) for modified-Truog extractable P, inorganic P and total P at either the 0- to 15- cm or 15- to 30- cm soil depth in either years. The means for modified-Truog extractable P, inorganic P and total P at the 0- to 15- cm depth were 19 (SE = 4), 592 (SE = 154), and 1594 (SE = 179) mg P kg$^{-1}$ respectively in year 6 while the means at the 15- to 30- cm depth were 17 (SE = 3), 499 (SE = 135), and 1328 (SE = 120) mg P kg$^{-1}$. There were no indications of foliar P deficiencies (Drechsel and Zech, 1991) at these levels of Modified-Truog (agronomic soil test) P as Senock (2003, unpublished data, California State Univ., Chico) found that SBG in SBG→SBG and ALB→SBG had leaf tissue P concentrations of 1.4 ± 0.2 g kg$^{-1}$ while ALB in SBG→ALB and ALB→ALB had concentrations of 1.6 ± 0.1 g kg$^{-1}$. The fact that P did not increase in soils during second rotation is result was in line with a resin bag study conducted by Binkley (unpublished, 2007), which showed that albizia did not increase soil P availability.

2.4 CONCLUSION

One of the primary effects of ALB in the first six years of the second rotation was to increase surface soil exchangeable bases (Ca, Mg, and K) to a depth of 15 cm in the SBG→ALB
rotation. Whether this increase can be maintained throughout the second rotation or whether it will decline due to soil acidification and subsequent base leaching induced by ALB N$_2$-fixation is unknown. A buildup of surface soil exchangeable bases for ALB was not present after 18 yr in the first rotation but ALB had decreased surface soil pH relative to SBG (Mathews et al., 2002; Table 2.1). The surface soil buildup of total N in the SBG→ALB rotation was expected as was total N decline or trends toward decline for the SBG→SBG and ALB→SBG rotations. N bioavailability is suspect for subsequent crops (Binkley, 1997). In a resin bag study by Binkley (unpublished, 2007), the nitrate data indicated that it is being released for soils under albizia, but for some reason not remaining in the soil after the second rotation. In the present study, after six years there was no difference between ALB→SBG and SBG→ALB for soil total N due to the opposite effects of ALB and SBG. It will be interesting to observe the ALB→ALB rotation to determine if soil total N accumulation has indeed reached a saturation point or a steady state condition.
CHAPTER 3: THE EFFECTS ON EARTHWORM ABUNDANCE AND BIOMASS IN A TROPICAL TREE PLANTATION IN A HYDRUDAND SOIL

3.1 INTRODUCTION

Earthworms are a major component of many terrestrial ecosystems (Edwards and Bohlen, 1996; Lavelle et al., 1998; Zou and Gonzalez, 2001) and often the most important animals influencing the functioning of soils (Hendrix and Bohlen, 2002) and they account for 40-90% macrofaunal biomass in most ecosystems with the exception of annually cropped systems (Fragoso, et al. 1999). Based on their feeding and burrowing activities, earthworms redistribute organic materials within the soil, increase soil penetrability (Syers and Springett, 1984), accelerate the decomposition of soil organic matter thereby increasing soil fertility (Zou and Gonzalez, 2001; Chauhan, 2014).

The abundance and species of earthworm communities are influenced by various factors. These factors include soil type, topography, vegetation, land use history and earthworm biogeography (Bohlen, 2002, González et al. (2006)). Tree species have also been shown to effect the abundance of earthworms, possibly through their leaf litter. In Hawaii, earthworm biomass increased up to 3-fold under the invasive N-fixing Myrica faya tree in comparison to open habitats and native rainforest communities; this difference was possibly attributed to increased litter production and/or the introduction of nitrogen rich-litter to the forest floor (Aplet, 1990).

The number of rotations under a given tree crop may also affect earthworm abundance. In a 18-yr Hawai‘i study on an Akaka silty clay loam (Acrudoxic Hydrudand) formerly cropped to sugarcane, Mathews et al. (2002) observed a differential soil N accumulation for first-rotation, dependent on tree species, N-fixing albizia [ALB, Falcataria moluccana (Miquel) Barneby & J.W. Grimes] or Sydney blue gum [SBG, Eucalyptus saligna (Sm.)]. While earthworms were not
measured in that first rotation, it is known that soil N availability can affect earthworm abundance (Bohlen et al., 2004). In this study, a unique opportunity exists on Hawaii Island to study earthworm invasion following conversion in land use from sugarcane to tree plantations and from the first to the second rotation with the same or different tree species. To our knowledge, no replicated studies have been conducted in the tropics to examine effects of second-rotation tree species on earthworm abundance and diversity. In this study, we used a reciprocal experiment of tree species to examine the effects of tree plantation rotation on earthworm abundance and biomass on the Island of Hawaii.

3.2 METHODS

Site Description

See Chapter 2.2 for site description, experimental design and soil sampling and analysis.

Earthworm Sampling

Earthworms were sampled in April and August 2007. Three soil pits (0.5 × 0.5 m) were established in each plot and the top 25 cm of soil was removed as quickly as possible. Earthworms were hand-sorted and stored in a plastic bag with ice in a cooler. Earthworm number accounting, species identification and fresh biomass weighing were carried out at the same date as the field sampling occurred.

Statistical Analyses

Data were analyzed by PROC GLM of the Statistical Analysis System (SAS Institute, 2003) using the appropriate models for a generalized randomized block design (GRBD). The site is the block effect and rotation effects are completely randomized within each site (Hinkelmann and Kempthorne, 1994). For soil, rotation means were separated using Fisher’s protected LSD
test at $P = 0.05$ (Gomez and Gomez, 1984). For the biomass and numbers of earthworms, three-way ANOVA with rotation site and season as factors showed that the site effect and its interactions were not significant thus, the data from the two sites were combined, analyzed using two-way ANOVA, and the treatment means were compared using Tukey’s HSD test at significance level of 0.05. To examine the relationships between earthworms and environmental factors, we computed Pearson product-moment correlation coefficients (SAS, 2003). The sample size in the correlation analysis was 16 (4 treatments with 4 replicates in each treatment).

3.3 RESULTS AND DISCUSSION

Two species, *Pontoscolex corethrurus* (Müller 1856) and *Amynthas gracilis* (Kinberg 1867), were found in all the treatments at the two locations. *P. corethrurus* is very adaptable and can be found around the world in moist tropical regions (Fragoso et al, 1999). *P. corethrurus* is an endogeic earthworm that feeds primarily on soil (Zou and Bashkin, 1998) and facilitates the breakdown and mineralization of surface litter. *A. gracilis* is an anecic earthworm that mainly feeds on surface litter (Zou and Bashkin, 1998) which it incorporates deep into the soil.

Both the density and the biomass did not differ between April and August samplings except for the density of species *A. gracilis* which was higher ($F = 5.74$, $p = 0.024$) in August (Fig. 3.1). The density of *A. gracilis* was affected by rotation ($F = 5.47$, $p = 0.005$), being greater in ALB→ALB than SBG→SBG and ALB→SBG. The biomass of *A. gracilis* was similarly affected ($F = 10.34$, $p < 0.001$) and was greater in ALB→ALB than in the other treatments. Both density ($F = 14.82$, $p < 0.001$) and biomass ($F = 13.47$, $p < 0.001$) of *P. corethrurus* were also affected by rotation and were greater in ALB→ALB than the other treatments (Fig. 3.1).
Site (p > 0.10) and the interaction of rotation and site effects (p > 0.15) were not significant for any of the soil chemical data but there were significant (p < 0.05) treatment effects for all the soil parameters with the exception of exchangeable Al\(^{3+}\) and SOC (p ≥ 0.10). Treatment means for soil data are presented in Table 3.1. Treatments SBG→SBG and SBG→ALB had greater pH values than treatment ALB→ALB while ALB→ALB tended (p = 0.10) to have greater SOC than SBG→SBG. For soil total N the differences were ALB→ALB>ALB→SBG>SBG→SBG while SBG→ALB was greater than SBG→SBG but did not differ from ALB→ALB or ALB→SBG. Treatments ALB→ALB and ALB→SBG had greater mineralizable N than SBG→SBG. There were no clear patterns in exchangeable cations among the treatments although SBG→ALB was higher in exchangeable Ca\(^{2+}\) and Mg\(^{2+}\) than the other treatments. The factors contributing to this exchangeable Ca\(^{2+}\) and Mg\(^{2+}\) response for SBG→ALB are difficult to explain but may be due in part to the young albizia trees serving as a source of N and readily decomposed organic matter to accelerate microbial turnover of more recalcitrant Eucalyptus derived organic matter containing Ca and Mg taken up during the first rotation (Briones and Ineson, 1996).

Both density (r = 0.51, p = 0.04) and biomass (r = 0.54, p = 0.02) of *A. gracilis* and *P. corethrurus* were positively correlated with soil mineralizable N. Density (r = 0.55, p = 0.03) and biomass (r = 0.64, p = 0.008) of *A. gracilis* were also positively correlated with soil total N. No significant correlations were found between *A. gracilis* density and biomass and the soil chemistry variables. Both the density (r = -0.61, p = 0.01) and biomass (r = -0.68, p = 0.004) of *P. corethrurus* were negatively correlated with soil pH. Biomass of *P. corethrurus* was positively correlated (r = 0.50, p = 0.05) with exchangeable Al\(^{3+}\).
*F. moluccana* is a N-fixing tree and higher soil N contents were found in plots of the treatment ALB→ALB. This finding agrees with the report by Sarlo (2006) that tree species with higher N concentration in leaf litter increased earthworm biomass in soils. Our finding that the density and biomass of both earthworm species were positively correlated with mineralizable N may indicate that earthworm activity can stimulate the overall net mineralization of N in tropical plantations. Barrios et al. (2005) reported that *P. corethrurus* could stimulate soil N mineralization in the tropical Andean slash/mulch planted fallows of Colombia. Lavelle et al. (1992) found that endogeic earthworms played a significant role in controlling soil structure, SOM dynamics and N availability in the humid tropics. They reported that fresh casts of *P. corethrurus* feeding on the upper 10 cm of soil in a tropical secondary forest contained up to 133 g kg⁻¹ mineralizable N. Subler et al. (1998) claimed that earthworms increased the short-term availability of mineral N following the application of inorganic fertilizer either by reducing microbial biomass immobilization or by retarding loss of mineral N from the surface soil. However, that earthworm density and biomass was significantly greater in the ALB→ALB treatment but not in the ALB→SBG suggests that the N enhancement by albizia might be limited in time. The second rotation was measured 3 years after planting, while the first rotation was 18 years.

The finding that both density and biomass of *P. corethrurus* were negatively correlated with pH was consistent with previous reports (e.g. Zou and Bashkin, 1998; Gonzalez et al., 1996; Smith et al., 2008). Biomass of *P. corethrurus* was also positively correlated with exchangeable Al³⁺ which tends to increase with decreasing pH (Mathews et al., 2002). This result may imply that soil pH could be a factor in triggering changes in endogeic worm numbers and *P. corethrurus* is well adapted to low pH soils. The result that there was no difference in density and biomass of
earthworms (except for *A. gracilis* in August) between April and August was not surprising considering that there are generally not substantial spring-summer seasonal changes in Hawaii.

However, other nutrients were not correlated with the earthworm measurements in this study. We did not find a significant correlation between earthworm density and biomass and SOC. In contrast, some previous findings in tropical forests showed earthworm density was positively correlated with SOC (e.g., Pashanasi et al., 1992; Zou, 1993; Gonzalez and Zou, 1999; Li et al., 2005). This result probably occurred because the relatively high SOC storage (over 130 g kg$^{-1}$) in all the treatments of the study sites and earthworm population was not limited by soil carbon. We also saw no relationship between cations and earthworms; a few previous studies reported decreases in exchangeable Ca$^{2+}$ and Mg$^{2+}$ concentrations associated with an increase in abundance of anecic earthworms in the tropics (Fragoso and Lavelle, 1992; Zou and Bashkin, 1998. Lavelle et al. (1992) reported that endogeic earthworms were affected by P in Alfisol and vertisol soils. We did not find a positive correlation between the density/biomass of earthworms and total P for our Andisol soil which contained considerable P.

It should be noted that earthworms were weighed with gut contents. This may be a factor contributing to the variation of the results because the gut contents of endogeic and anecic species are of different materials and mass. The earthworm density and biomass may have also been influenced by the application of herbicide after harvesting the first rotation trees (Mathews, 2002).

3.4 CONCLUSION

Both earthworm species had greater densities and biomass in the treatment ALB→ALB than in the other treatments. Also, soil N was positively correlated with the density and biomass
of both *A. gracilis* and *P. corethrurus* species. These findings indicate that N may have been a limiting factor to earthworm population growth and there may have been effects of first-rotation tree species on earthworm density and biomass. Alternatively, it may be that the high quality litter of *F. moluccana* has an effect on the earthworm dynamics if provided a long enough time period. This study provided important information on earthworm dynamics in Hawaiian ecosystems because there are few studies reporting data on earthworm communities from different land uses in Hawaii. This study is especially important because Hawaii had no earthworms prior to human colonization, and is now populated by a variety of exotic earthworm species (Nakamura, 1990).
CHAPTER 4: CONCLUSION

Both eucalyptus and albizia are commonly used tropical tree plantation species due to their fast growth. Eucalyptus high yield (DeBell et al., 1989) serves as a source of wood pulp and for bioenergy, and albizia provides a biological source of nitrogen input. Using them together can help replenish soil fertility, specifically nitrogen, but the order of planting may influence the maintenance soil fertility.

In the first study, we examined species effects on soil fertility between first and second rotations. We hypothesized that N enrichment would increase if an N-fixing species was again used during the second rotation. However, there was no increase in total soil N. Therefore, the use of albizia as long-term N-enrichment strategy may not be effective, at least on the time scale of the 18-yr interval between rotations. In addition, total soil N did not increase when the second species was albizia.

In the second study, we hypothesized that the use of an N-fixing species would enrich the soil in the second rotation, influencing earthworm populations. However, there was no increase in earthworm density or biomass in the treatments with ALB→SBG. Therefore, this planting strategy may not be the most effective for enhancing soil invertebrates.

Questions that remain to be answered would be: 1) what are dominant forms of nitrogen generated from the albizia, because organic N was not measured in this study, and 2) the length of time for which the N sourced from albizia remains in the soil. It should also be noted that the two studies in this thesis were not sampled at the same time in the field (1 mo apart), and a future study could test if this timing is important. In addition, intercropping of the two species, rather than planting them in succession may be a useful way to increase soil fertility. It is also important to note that albizia is an invasive species in Hawai‘i. It poses a known potential
negative impact to native systems (Aplet, 1990) therefore, this risk factor should be considered before using it for agroforestry purposes.
### Table 2.1: Mean Alaska soil pH in water, Modified-Tueng extractable P, exchangeable cations, effective cation exchange capacity (ECCE), Al saturation (Al\textsubscript{sat}), organic carbon (OC), and total N (TN) for the Sydney blue gum (SBG) and albizia (ALB) plots one year prior to planting the second rotation. Standard deviations are in parentheses. Data are from Matthews et al. (2002).

<table>
<thead>
<tr>
<th>Depth</th>
<th>pH\textsubscript{w}</th>
<th>P</th>
<th>Ca\textsuperscript{2+}</th>
<th>Mg\textsuperscript{2+}</th>
<th>K\textsuperscript{+}</th>
<th>Al\textsuperscript{3+}</th>
<th>ECCE</th>
<th>Al\textsubscript{sat}</th>
<th>OC</th>
<th>TN</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 15 cm</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SBG</td>
<td>4.6</td>
<td>4.1 (1.7)</td>
<td>6.7 (2.1)</td>
<td>1.4 (0.4)</td>
<td>7.0 (4.1)</td>
<td>19.2 (5.8)</td>
<td>34 (18)</td>
<td>120 (7)</td>
<td>120 (7)</td>
<td>7.4 (0.3)</td>
</tr>
<tr>
<td>ALB</td>
<td>4.4</td>
<td>4.4 (2.3)</td>
<td>7.9 (3.7)</td>
<td>1.6 (0.5)</td>
<td>8.7 (5.5)</td>
<td>22.6 (7.1)</td>
<td>37 (19)</td>
<td>172 (9)</td>
<td>172 (9)</td>
<td>11.2 (0.8)</td>
</tr>
<tr>
<td>15 to 30 cm</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SBG</td>
<td>4.8</td>
<td>3.5 (2.3)</td>
<td>5.4 (1.5)</td>
<td>1.2 (0.3)</td>
<td>4.2 (1.6)</td>
<td>14.4 (4.5)</td>
<td>30 (9)</td>
<td>100 (10)</td>
<td>100 (10)</td>
<td>5.9 (0.6)</td>
</tr>
<tr>
<td>ALB</td>
<td>4.6</td>
<td>2.9 (1.0)</td>
<td>5.8 (1.2)</td>
<td>1.3 (0.5)</td>
<td>5.2 (2.7)</td>
<td>14.8 (3.5)</td>
<td>34 (10)</td>
<td>102 (11)</td>
<td>102 (11)</td>
<td>6.8 (0.6)</td>
</tr>
</tbody>
</table>
Table 2.2. Sydney blue gum to Sydney blue gum (SBG-SBG), albacia to albacia (ALB-ALB), Sydney blue gum to albacia (SBG-ALB), and albacia to Sydney blue gum (ALB-SBG) rotation effects on soil pH, concentrations of exchangeable cations, effective cation exchange capacity (ECCE) and aluminium saturation (Al\textsubscript{sat}) in the topsoil (0- to 15-cm depth) in year 3 and 6 of the second rotation. Table from Shimizu-Kuroko et al. (2009).

<table>
<thead>
<tr>
<th>Rotation</th>
<th>pH</th>
<th>Ca\textsuperscript{2+}</th>
<th>Mg\textsuperscript{2+}</th>
<th>K\textsuperscript{+}</th>
<th>Al\textsuperscript{3+}</th>
<th>ECCE</th>
<th>Al\textsubscript{sat}</th>
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<tr>
<td>Yr 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SBG-SBG</td>
<td>4.6a</td>
<td>2.0b</td>
<td>3.0b</td>
<td>0.5c</td>
<td>9.5a</td>
<td>16.1a</td>
<td>56.6a</td>
</tr>
<tr>
<td>ALB-ALB</td>
<td>4.4b</td>
<td>3.6b</td>
<td>3.3b</td>
<td>0.6a</td>
<td>13.1a</td>
<td>21.0ab</td>
<td>69.4a</td>
</tr>
<tr>
<td>SBG-ALB</td>
<td>4.7a</td>
<td>8.5a</td>
<td>6.1a</td>
<td>0.7a</td>
<td>7.0a</td>
<td>22.4a</td>
<td>30.8b</td>
</tr>
<tr>
<td>ALB-SBG</td>
<td>4.4b</td>
<td>2.1b</td>
<td>2.8b</td>
<td>0.6a</td>
<td>10.6a</td>
<td>16.7b</td>
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</tr>
<tr>
<td>Mean</td>
<td>4.5</td>
<td>4.2</td>
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<td>0.7</td>
<td>10.0</td>
<td>18.9</td>
<td>53.7</td>
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<tr>
<td>SE\textsuperscript{†}</td>
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<td>0.7</td>
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<td>1.8</td>
<td>1.7</td>
</tr>
<tr>
<td>Yr 6</td>
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<tr>
<td>SBG-SBG</td>
<td>4.6a</td>
<td>3.8b</td>
<td>4.3b</td>
<td>1.2c</td>
<td>9.1a</td>
<td>18.4b</td>
<td>52.0a</td>
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<tr>
<td>ALB-ALB</td>
<td>4.4b</td>
<td>3.6b</td>
<td>4.1b</td>
<td>1.5bc</td>
<td>9.6a</td>
<td>18.5b</td>
<td>48.1a</td>
</tr>
<tr>
<td>SBG-ALB</td>
<td>4.8a</td>
<td>14.7a</td>
<td>8.5a</td>
<td>1.2c</td>
<td>5.3a</td>
<td>30.2a</td>
<td>17.9b</td>
</tr>
<tr>
<td>ALB-SBG</td>
<td>4.5b</td>
<td>2.5b</td>
<td>3.5b</td>
<td>1.4e</td>
<td>10.9a</td>
<td>17.8b</td>
<td>59.5a</td>
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<tr>
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<td>5.1</td>
<td>1.4</td>
<td>8.7</td>
<td>21.3</td>
<td>44.4</td>
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<tr>
<td>SE\textsuperscript{‡}</td>
<td></td>
<td>1.4</td>
<td>1.0</td>
<td>0.1</td>
<td>2.0</td>
<td>1.6</td>
<td>7.9</td>
</tr>
</tbody>
</table>

\* Rotation means in the same column and year not followed by a common letter are different at P < 0.05 using Fisher’s F-test protected LSD test, except for pH, where P is < 0.10.

\* Standard error of a rotation mean.

+ *, **, *** Significant at the 0.10, 0.05, 0.01, and 0.001 probability levels respectively, or NS (non-significant) P > 0.10.
Table 2.3. Sydney blue gum to Sydney blue gum (SBG-SBG), albizia to albizia (ALB-ALB), Sydney blue gum to albizia (SBG-ALB), and albizia to Sydney blue gum (ALB-SBG) rotation effects on soil pH, concentrations of exchangeable cations, effective cation exchange capacity (ECEC) and aluminium saturation (Al\textsubscript{Al}) in the subsoil (15- to 30-cm depth) in yr 3 and 6 of the second rotation. Table from Shimabukuro-Madden et al. (2009).

<table>
<thead>
<tr>
<th>Rotation</th>
<th>pH</th>
<th>Ca\textsuperscript{2+}</th>
<th>Mg\textsuperscript{2+}</th>
<th>K\textsuperscript{+}</th>
<th>Al\textsuperscript{3+}</th>
<th>ECEC</th>
<th>Al\textsubscript{Al}</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>(mmol-h\textsubscript{kg}^{-1})</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Yr 3</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SBG-SBG</td>
<td>4.8 ± 1</td>
<td>0.6a</td>
<td>1.2b</td>
<td>0.2a</td>
<td>4.0a</td>
<td>6.0a</td>
<td>63.4a</td>
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<tr>
<td>ALB-ALB</td>
<td>4.8 ± 1</td>
<td>0.9c</td>
<td>1.2b</td>
<td>0.6a</td>
<td>2.8a</td>
<td>5.5a</td>
<td>49.3a</td>
</tr>
<tr>
<td>SBG-ALB</td>
<td>5.0 ± 1</td>
<td>2.5a</td>
<td>2.2a</td>
<td>0.3a</td>
<td>3.1a</td>
<td>6.9a</td>
<td>31.4a</td>
</tr>
<tr>
<td>ALB-SBG</td>
<td>4.8 ± 1</td>
<td>0.8c</td>
<td>1.0b</td>
<td>0.2a</td>
<td>3.6a</td>
<td>5.4a</td>
<td>63.9a</td>
</tr>
<tr>
<td>Mean</td>
<td>4.9 ± 1</td>
<td>1.1c</td>
<td>1.4a</td>
<td>0.3</td>
<td>3.1a</td>
<td>5.9</td>
<td>52.0</td>
</tr>
<tr>
<td>SBG</td>
<td>-</td>
<td>0.3</td>
<td>0.2</td>
<td>0.2</td>
<td>0.8</td>
<td>0.6</td>
<td>10.6</td>
</tr>
</tbody>
</table>

| Yr 6         |     |                        |                        |                      |                        |      |                      |
| SBG-SBG      | 4.7 ± 1 | 1.3b                 | 1.8b                   | 0.8a                 | 5.2a                   | 9.0a | 57.4a                |
| ALB-ALB      | 4.7 ± 1 | 0.9c                 | 1.8b                   | 0.8a                 | 2.2a                   | 7.2a | 31.8a                |
| SBG-ALB      | 5.0 ± 1 | 3.9c                 | 2.5a                   | 0.9a                 | 2.0a                   | 9.4a | 20.6a                |
| ALB-SBG      | 4.6 ± 1 | 0.7c                 | 1.2b                   | 0.8a                 | 6.1a                   | 8.9a | 64.6a                |
| Mean         | 4.7 ± 1 | 1.7                  | 1.7                    | 0.8                  | 5.1                    | 9.4  | 51.6                 |
| SBG         | -    | 0.5                  | 0.3                    | 0.1                  | 1.9                    | 1.6  | 10.4                 |

* Year effect

* Rotation means in the same column and year not followed by a common letter are different at *P* < 0.05 using Fisher’s F-test protected LSD test, except for Al\textsubscript{Al} in yr 6 where *P* is < 0.1.  
† Standard error of a rotation mean.  
* | ** | * | *** | | NS  
|---|---|---|---|---|---|

* * | Significant at the 0.05, 0.01, and 0.001 probability levels, respectively, or NS (non-significant *P* > 0.10)
Table 2.4. Sydney blue gum to Sydney blue gum (SBG-SBG), albizia to albizia (ALB-ALB), Sydney blue gum to albizia (SBG-ALB), and albizia to Sydney blue gum (ALB-SBG) rotation effects on soil total organic carbon (OC), OC gain since the first rotation, total N, total N gain/loss since the first rotation, G:N ratio, 1M KCl extractable NH$_4^-$N and NO$_3^-$N, and readily mineralizable N (RMN) in the topsoil (0-15 cm depth) in year 3 and 6. Table from Shimabukuro et al. (2009).

<table>
<thead>
<tr>
<th>Rotation</th>
<th>OC (g kg$^{-1}$)</th>
<th>OC gain (Mg ha$^{-1}$)</th>
<th>Total N (g kg$^{-1}$)</th>
<th>Total N gain/loss (Mg ha$^{-1}$)</th>
<th>C:N ratio</th>
<th>NH$_4^-$ N (mg kg$^{-1}$)</th>
<th>NO$_3^-$ N (mg kg$^{-1}$)</th>
<th>RMN (mg kg$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SBG-SBG</td>
<td>135.3a†</td>
<td>11.06a</td>
<td>8.0b</td>
<td>0.43a</td>
<td>16.9a</td>
<td>16a</td>
<td>15a</td>
<td>104b</td>
</tr>
<tr>
<td>ALB-ALB</td>
<td>147.2a</td>
<td>18.13a</td>
<td>9.8a</td>
<td>1.12a</td>
<td>15.1b</td>
<td>21a</td>
<td>28a</td>
<td>142a</td>
</tr>
<tr>
<td>SBG-ALB</td>
<td>140.9a</td>
<td>15.07a</td>
<td>8.4b</td>
<td>0.72a</td>
<td>16.8a</td>
<td>19a</td>
<td>22a</td>
<td>108b</td>
</tr>
<tr>
<td>ALB-SBG</td>
<td>148.8a</td>
<td>19.28a</td>
<td>9.7a</td>
<td>1.04a</td>
<td>15.5b</td>
<td>10a</td>
<td>29a</td>
<td>129a</td>
</tr>
<tr>
<td>Mean</td>
<td>143.0</td>
<td>15.87</td>
<td>9.0</td>
<td>0.83</td>
<td>16.1</td>
<td>16</td>
<td>24</td>
<td>121</td>
</tr>
<tr>
<td>SE†</td>
<td>4.9</td>
<td>3.52</td>
<td>0.3</td>
<td>0.24</td>
<td>0.3</td>
<td>4</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>2007</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SBG-SBG</td>
<td>131.1b</td>
<td>7.97b</td>
<td>7.1c</td>
<td>-0.22b</td>
<td>18.5a</td>
<td>15a</td>
<td>25c</td>
<td>113b</td>
</tr>
<tr>
<td>ALB-ALB</td>
<td>147.5a</td>
<td>18.38a</td>
<td>9.2a</td>
<td>0.72a</td>
<td>16.1b</td>
<td>14a</td>
<td>50a</td>
<td>154a</td>
</tr>
<tr>
<td>SBG-ALB</td>
<td>142.9ab</td>
<td>16.51a</td>
<td>8.6ab</td>
<td>0.85a</td>
<td>16.7b</td>
<td>18a</td>
<td>41ab</td>
<td>134ab</td>
</tr>
<tr>
<td>ALB-SBG</td>
<td>139.3ab</td>
<td>12.44ab</td>
<td>8.2b</td>
<td>0b</td>
<td>17.0b</td>
<td>10a</td>
<td>33bc</td>
<td>142a</td>
</tr>
<tr>
<td>Mean</td>
<td>140.2</td>
<td>13.82</td>
<td>8.3</td>
<td>0.34</td>
<td>17.1</td>
<td>14</td>
<td>37</td>
<td>136</td>
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<tr>
<td>SE†</td>
<td>4.0</td>
<td>2.89</td>
<td>0.3</td>
<td>0.18</td>
<td>0.5</td>
<td>3</td>
<td>4</td>
<td>8</td>
</tr>
</tbody>
</table>

† Rotation means in the same column and year not followed by a common letter are different at $P < 0.05$ using Fisher's F-test protected LSD test, except for OC and OC gain in 2007 where $P < 0.10$.
‡ Standard error of a rotation mean.
§ Significant at the 0.10, 0.01, and 0.001 probability levels respectively, or NS (non-significant $P > 0.10$).
Table 2.5. Sydney blue gum to Sydney blue gum (SBG-SBG), albizia to albizia (ALB-ALB), Sydney blue gum to albizia (SBG-ALB), and albizia to Sydney blue gum (ALB-SBG) rotation effects on soil total organic carbon (OC), OC gain since the first rotation, total N, total N gain since the first rotation, C:N ratio, Ed-KCl extractable NH4-N and NO3-N, and readily mineralizable N (RMN) in the subsoil (15- to 30-cm depth) in yr 3 and 6 of the second rotation. Table from Shimabukuro-Maddox et al. (2009).

<table>
<thead>
<tr>
<th>Rotation</th>
<th>Yr 3</th>
<th></th>
<th>Yr 6</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OC g kg⁻¹</td>
<td>OC gain Mg ha⁻¹</td>
<td>Total N g kg⁻¹</td>
<td>Total N gain loss Mg ha⁻¹</td>
</tr>
<tr>
<td>SBG-SBG</td>
<td>100.2b†</td>
<td>6.21a</td>
<td>6.5a</td>
<td>0.39a</td>
</tr>
<tr>
<td>ALB-ALB</td>
<td>104.4b</td>
<td>6.04a</td>
<td>6.6a</td>
<td>0.17b</td>
</tr>
<tr>
<td>SBG-ALB</td>
<td>117.8a</td>
<td>11.58a</td>
<td>6.6a</td>
<td>0.47a</td>
</tr>
<tr>
<td>ALB-SBG</td>
<td>108.6b</td>
<td>4.44b</td>
<td>6.6a</td>
<td>0.15b</td>
</tr>
<tr>
<td>Mean</td>
<td>110.0</td>
<td>6.67</td>
<td>6.6</td>
<td>0.16</td>
</tr>
<tr>
<td>SE‡</td>
<td>2.9</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Yr 6</td>
<td></td>
</tr>
<tr>
<td>SBG-SBG</td>
<td>111.6a</td>
<td>7.81a</td>
<td>6.06e</td>
<td>0.07a</td>
</tr>
<tr>
<td>ALB-ALB</td>
<td>112.1a</td>
<td>6.83a</td>
<td>6.65b</td>
<td>0.24a</td>
</tr>
<tr>
<td>SBG-ALB</td>
<td>106.0a</td>
<td>4.05a</td>
<td>5.8c</td>
<td>0a</td>
</tr>
<tr>
<td>ALB-SBG</td>
<td>110.5a</td>
<td>9.79a</td>
<td>6.6a</td>
<td>0.15a</td>
</tr>
<tr>
<td>Mean</td>
<td>111.6</td>
<td>7.12</td>
<td>6.2</td>
<td>0.08</td>
</tr>
<tr>
<td>SE‡</td>
<td>2.7</td>
<td>1.60</td>
<td>0.2</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>NS</td>
<td>NS</td>
<td>**</td>
<td>**</td>
</tr>
</tbody>
</table>

† Rotation means in the same column and year not followed by a common letter are different at P < 0.05 using Fisher's F-test protected LSD test, except for OC in yr 3 and total N in yr 6, where P < 0.10.
‡ Standard error of a rotation mean.
*, **, ***Significant at the 0.10, 0.05, and 0.001 probability levels respectively, or NS (non-significant P > 0.10).
Table 3.1: Mean values of soil chemistry variables in the four treatments: Sydney blue gum to Sydney blue gum (SBG→SBG), albizia to albizia (ALB→ALB), Sydney blue gum to albizia (SBG→ALB), and albizia to Sydney blue gum (ALB→SBG). Common letters within a column indicate no significant difference (P<0.05) using Fisher’s F-test Table from Li et al. (2010).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>pH</th>
<th>SOC (g kg⁻¹)</th>
<th>Total N (g kg⁻¹)</th>
<th>Nitr N (mg kg⁻¹)</th>
<th>Ca²⁺ (mmol kg⁻¹)</th>
<th>Mg²⁺ (mmol kg⁻¹)</th>
<th>K⁺ (mmol kg⁻¹)</th>
<th>Al³⁺ (mmol kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBG→SBG</td>
<td>4.6a</td>
<td>131.1a</td>
<td>7.1c</td>
<td>117b</td>
<td>3.8b</td>
<td>4.3b</td>
<td>1.2c</td>
<td>9.1a</td>
</tr>
<tr>
<td>ALB→ALB</td>
<td>4.5b</td>
<td>147.5a</td>
<td>9.2a</td>
<td>154a</td>
<td>3.6b</td>
<td>4.1b</td>
<td>1.5ab</td>
<td>9.6a</td>
</tr>
<tr>
<td>SBG→ALB</td>
<td>4.8b</td>
<td>142.6a</td>
<td>8.6ab</td>
<td>134ab</td>
<td>14.7a</td>
<td>8.5a</td>
<td>1.7a</td>
<td>5.3a</td>
</tr>
<tr>
<td>ALB→SBG</td>
<td>4.5ab</td>
<td>135.6a</td>
<td>8.2b</td>
<td>145a</td>
<td>2.0b</td>
<td>3.5b</td>
<td>1.4bc</td>
<td>10.5a</td>
</tr>
</tbody>
</table>
Fig. 3.1. Earthworm mean density and biomass for species *P. corethrurus* and *A. gracilis* in four treatments: *Eucalyptus saligna* to *E. saligna* (SBG→SBG), *Falcataria moluccana* to *F. moluccana* (ALB→ALB), *E. saligna* to *F. moluccana* (SBG→ALB) and *F. moluccana* to *E. saligna* (ALB→SBG). Treatments marked with the same letter do not differ significantly. Season was significant only for *A. gracilis* which was more abundant in August than in April (Li et al., 2010).
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