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Soil Chemistry Following Afforestation of Barren Coastal Soils in Southern Guam Does Not Conform to that of Continuously Vegetated Surfaces

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Abstract

The chemical changes in soils following the use of non-native *Acacia* trees to mitigate soil erosion from barren scars within Guam's grassland savanna were determined and compared to continuously vegetated sites. Chemistry of the soils in a 20-yr-old *Acacia* site was dissimilar to that of the grasslands and adjacent native forest sites. Stoichiometry calculations which characterize ecosystem function were unique within the *Acacia* site. Watershed management decisions that convert previous grasslands to exotic tree forests may have long-term effects on soil nutrients and create unique soil nutrient budgets. Increased knowledge of all affected ecological processes and embracing social sciences to include human behavior traits are needed to better inform Guam's ecosystem management decisions.

Keywords: *Acacia*; Afforestation; Mineralization; Plant soil feedback; Stoichiometry

Introduction

Non-forested vegetation types on acid soils in Micronesia are dominated by grasslands [1]. These grasslands are called savanna in Guam, and their integrity is vulnerable to anthropogenic disturbances such that large barren scars develop where exposed degradation or aggradation is sustained. Human activities such as off-road locomotive use and purposeful setting of wild land fires are frequent genesis activities, and once initiated these "badlands" generally do not become re-vegetated without intervention [2].

Health of the coastal ecosystems of all Micronesian islands is tightly linked to health of the watersheds, and these badlands pose chronic threats to the health of coastal biota due to sedimentation of eroded materials. Planting tree seedlings in the badland areas has been employed for several Guam watersheds, and reduced erosion has been documented as a result [2,3].

To my knowledge, no detailed comparison of soil chemical traits has been conducted among intact vegetated surfaces and barren surfaces in southern Guam. My primary objective was to determine changes in soil chemical traits following the use of non-native *Acacia* species to recover badlands in southern Guam. The secondary objective was to determine the soil trait differences between Guam's undisturbed savanna grassland and adjacent native forests.

Materials and Methods

Study site

The coastal site was 70-85 m above sea level and was located ca. 1.8 km from the southern coast of Guam. The dominant soil in the location was Akina series (Very fine, kaolinitic, isohyperthermic, Oxic Haplustalfs), an erodible substrate of pyroclastic origin [4]. A barren area approximately 5,000 m^2 was planted with a mixture of *Acacia auriculiformis, Acacia mangium, Casuarina equisetifolia,* and *Eucalyptus sp.* in 1994. The two *Acacia* species out-competed the other species and most of the *Casuarina equisetifolia* and *Eucalyptus* died within 10 years. The remaining trees were culled in 2004 to create a pure *Acacia* stand comprised of *A.auriculiformis, A.mangium* and recruits that were partly inter-specific hybrids. The afforestation fragment was 5,750 m^2 at the time of the sampling in 2014.

Badlands, native forest fragments in deep ravines, and grasslands are ubiquitous in many southern Guam locations, so the *Acacia* afforestation fragment was used as the fixed site for sampling. The closest barren badland area approximating the size of the *Acacia* fragment was located approximately 500 metres to the north and was selected for the badland samples. The Ajayan watershed was located to the west of the *Acacia* fragment, and native forest samples were obtained from a site on the east flanks of this watershed approximately 600 metres to the north-west. The undisturbed native forest was characterized by *Cocos nucifera, Cynometra ramiflora, Cycas micronesica, Hibiscus tiliaceus,* and *Pandanus tectorius.* Several exotic tree species were prevalent in the forest, but the sites with exotic species were avoided for sample collection. The intact native forests in this location were not on pure Akina soils, but were an Akina-Agfayan-Rock complex. The Agfayan series is similar to Akina (Clayey, montmorillonitic, ishyperthermic, shallow Udic Haplustolls). The undisturbed grassland samples were obtained approximately in the center of the space delimited by the other three sites. The dominant graminoid where samples were collected was *Miscanthus floridulus.*

Sampling

All samples were collected on 13 September 2014. The *Acacia* forest fragment and the badland fragment were divided into three relatively equal sections. Ten samples were taken from each of these sections as 0-15 cm composites. The grassland and native forest was sampled as three sites separated by 50 metres and 10 soils samples were collected from each site and homogenized. Sampling in the expansive native forest and grasslands was confined to approximately the same area as the areas of the badland and *Acacia* fragments. Therefore, there were three replications from each site, each comprised of 10 soil samples.

Each sample collected for nitrate and ammonium determination

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was divided into two samples. One sample was immediately placed within frozen ice packs within a cooler. These samples were transferred to a freezer for storage on the same day. The other sample was used for incubation using the buried bag method [5] in each of the 12 sampling sites for 36 days. Following retrieval, the post-incubation samples were also stored in the freezer until analysis.

Analyses

A portion of each sample was dried at 50°C then total carbon and nitrogen were determined by dry combustion [6] using a FLASH EA1112 CHN analyzer (Thermo Fisher, Waltham, Mass., USA). Extractable phosphorus was conducted using the modified Truog method [7], other macronutrients and micronutrients were extracted by diethylenetriaminepentaacetic acid [8], and metals were determined by nitric acid digestion [9]. Contents were determined by inductively coupled plasma optical emission spectrometry [10] with a Spectro Genesis analyzer (SPECTRO Analytical Instruments, Kleve, Germany). Nitrate and ammonium were determined colorimetrically from fresh moist soil samples following 2 M KCl extraction. Net nitrification was calculated by subtracting initial from final nitrate concentration and dividing by the incubation period. Net ammonification was calculated by subtracting initial from final ammonium concentration and dividing by the incubation period. Total net mineralization was calculated for the purposes of this paper as the sum of net nitrification and net ammonification. Stoichiometric calculations included C/N as total and N/P, N/K, and K/P as available/extractable.

Concentration, pH, and flux results met parametric prerequisites except for non-constant variances. Therefore, a mixed linear model was used (SAS Version 9.3, PROC MIXED) which is a generalization of the standard linear model employed in the PROC GLM procedure that takes into account non-equal variances. Stoichiometry variables were analysed by one-way analysis of variance following log-transformation using PROC GLM. Means separation for traits that were significant was conducted by Least Significant Difference.

Soil nitrogen trait	Barren badland	Savanna Grassland	*Acacia* forest	Intact native forest	Significance
Total N (mg g^{-1})	0.28A	18.65B	24.60B	24.09B	0.0050
Nitrate (μg g^{-1})	3.30C	2.37B	10.94C	0.11A	0.0297
Ammonium (μg g^{-1})	0.71A	8.40B	9.47B	39.12C	0.0502
Available N (μg g^{-1})	4.02A	10.77B	20.40C	39.23C	0.0400
Ammonification (μg g^{-1} d^{-1})	-0.05	0.11	-0.02	0.51	NS
Nitrification (μg g^{-1} d^{-1})	-0.01A	0.02A	1.19B	0.94B	0.0004
Mineralization (μg g^{-1} d^{-1})	-0.05A	0.12B	1.16C	1.45C	0.0035

Table 2: Nitrogen traits in acid volcanic soils in southern Guam under undisturbed grassland or forest conditions, and following disturbance to eroded badlands and afforestation mitigation. Numbers within rows followed by the same letter are not significantly different, n=3.

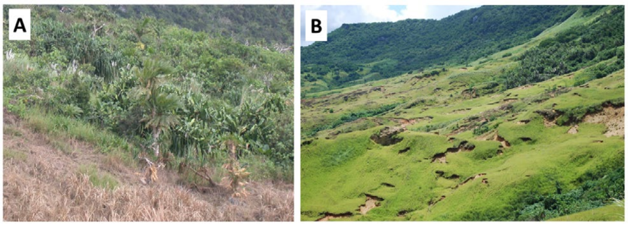

Figure 1: A) Ecotones that characterize the transition from Guam's savanna grasslands to native forest trees respond differently to fires. The grass species recover rapidly while the edge forest trees often die. B) Fires and other anthropogenic activities generate barren exposed sites within savanna habitats.

Soil trait (μg g^{-1})	Barren badland	Savanna grassland	*Acacia* forest	Intact native forest	Significance
Cadmium	0.10D	0.08C	0.02B	<0.01A	<0.0001
Cobalt	48.72C	47.95C	5.62A	24.64B	<0.0001
Chromium	24.04C	20.48B	17.96B	11.79A	0.0002
Copper	154.19C	136.45C	58.93A	81.38B	0.0003
Nickel	0.52B	1.10B	0.42A	7.92C	0.0048
Lead	0.01	0.01	0.01	<0.01	NS
Selenium	0.01	0.08	0.09	0.22	NS

Table 3: Concentration of metals in acid volcanic soils in southern Guam under undisturbed grassland or forest conditions, and following disturbance to eroded badlands and afforestation mitigation. Numbers within rows followed by the same letter are not significantly different, n=3.

Results

Nutrient concentrations and soil reaction

The relationships among the four sites were idiosyncratic for the measured nutrients (Table 1). The *Acacia* forest site aligned with the barren site for several traits such as pH and phosphorus (barren=*Acacia*<*grassland*<*native forest*) or manganese and iron (barren=*Acacia*<grassland=native forest). The *Acacia* forest site aligned with the grassland site for several other traits such as carbon and calcium (barren<*Acacia*=grassland<native forest). In contrast, the *Acacia* forest differed from all other sites for magnesium, potassium, and zinc. The various forms of soil nitrogen also exhibited mixed responses among the sites, but the *Acacia* site always aligned with at least one of the other vegetated sites (Table 2). Total nitrogen was greater in the three vegetated sites than the barren site, and did not differ among the vegetated sites. Net ammonification was minimal and was not different among the four sites. Available nitrogen and total net mineralization were least in the barren site and greatest in the two forest sites. Nitrate was least in the native forest site and greatest in the barren and *Acacia* forest sites (Figure 1). The *Acacia* forest site aligned with the grassland site for ammonium (barren<grassland=*Acacia*<native forest) and aligned with the native forest site for nitrification (barren=grassland<*Acacia*=native forest).

Soil trait	Barren badland	Savanna grassland	*Acacia* forest	Intact native forest	Significance
pH	4.56A	5.23B	4.48A	6.56C	0.0036
Carbon (mg g^{-1})	24.87A	346.24B	349.53B	640.69C	<0.0001
Phosphorus (μg g^{-1})	8.74A	24.06B	9.84A	46.36C	0.0085
Potassium (μg g^{-1})	153.82B	459.95C	86.75A	1875.24D	<0.0001
Calcium (μg g^{-1})	477.68A	1845.86B	2592.91B	7181.32C	0.0081
Magnesium (μg g^{-1})	3455.79BC	3914.91C	672.40A	3054.05B	0.0001
Manganese (μg g^{-1})	11.80A	74.41B	13.92A	46.16B	0.0013
Iron (μg g^{-1})	3.84A	48.35B	5.48A	73.34B	0.0040
Zinc (μg g^{-1})	0.47A	6.09C	1.37B	4.42C	0.0003

Table 1: Substrate pH and concentration of macronutrients and micronutrients in acid volcanic soils in southern Guam under undisturbed grassland or forest conditions, and following disturbance to eroded badlands and afforestation mitigation. Numbers within rows followed by the same letter are not significantly different, n=3.

Metal concentrations

The barren site exhibited the greatest cadmium, cobalt, chromium, and copper concentrations (Table 3). In contrast, the native forest site exhibited the greatest nickel concentration. Lead and selenium concentration did not differ among the four sites. Cadmium and chromium concentrations were least in the native forest site. Cobalt, copper, and nickel concentrations were least in the *Acacia* site.

Soil trait	Barren badland	Savanna grassland	*Acacia* forest	Intact native forest	Significance
C/N	89.86D	18.56B	14.21A	28.68C	<0.0001
N/P	0.46A	0.45A	2.05C	0.85B	<0.0001
N/K	0.03A	0.02A	0.23B	0.02A	<0.0001
K/P	17.61B	19.12B	8.82A	40.88C	<0.0001

Table 4: C:N:P:K stoichiometry in acid volcanic soils in southern Guam under undisturbed grassland or forest conditions, and following disturbance to eroded badlands and afforestation mitigation. C/N based on total concentration. N/P, N/K, and K/P based on extractable content. Numbers within rows followed by the same letter are not significantly different, n=3.

Stoichiometry

Soil C/N was greatest in the barren site (*Acacia*<grassland<native forest<barren). In contrast, soil N/P and N/K were greatest in the *Acacia* site (Table 4). Soil K/P exhibited the most unusual pattern with the two forest sites exhibiting the least and greatest quotients (*Acacia*<barren=savanna<native forest).

Discussion

A chronological approach may be applied to three of the sites, where intact grassland was followed by erosion to barren badlands then mitigation to *Acacia* afforestation. The motivation for using *Acacia* trees to recover badlands is to regain the soil retention properties of the grassland sites in order to reduce badland erosion, and thereby reduce sedimentation in river and coastal ecosystems [2,3]. These results indicate that soil chemical traits that are modified by development of barren badlands from savanna were not reversed following 20 years under *Acacia* cover. These included iron, manganese, nitrate, pH, and phosphorus. Moreover, the stoichiometric traits exhibited substantial contrast among the grassland, barren, and *Acacia* sites, further revealing that soil chemical traits that influence ecosystem function diverged during the use of *Acacia* trees to mitigate erosion in the badlands. In contrast to the many traits that were dissimilar, *Acacia* plantings did return several soil chemical traits to those of the intact grasslands. For example, carbon, calcium, total nitrogen, and ammonium were decreased in badland scars, and then increased in *Acacia* forest in a manner that returned to levels in original grasslands.

Mitigation of badlands with exotic *Acacia* trees may also be justified for ecological restoration if traits of the afforestation sites are directed toward those of nearby native forest sites. However, all soil chemical traits in the *Acacia* forest differed from those in the native forest with the exception of four of the nitrogen traits. The stoichiometry traits were among those that were highly contrasting between the two forest types. Based on these results, 20 years of *Acacia* forest development in southern Guam may reverse soil erosion from badlands, but it does not return soil chemical properties to levels similar to savanna or native forest sites.

Two of my sites were useful for comparing intact savanna and intact native forest in the absence of evident recent disturbance. These two undisturbed sites were separated by less than 300 m, yet the soil traits were highly contrasting. Only four of the nutrients and two of the metals were similar between these two vegetation types. The majority of the measured and calculated soil chemical traits were greater in the native forest site than in the grassland site.

Net ammonification was remarkably constrained among all four sites. Net nitrification was similarly constrained in the badland and grassland sites, but was considerable in the two forest sites. These results indicate that within two decades, *Acacia* plantings sustain considerable Nitrosomas and Notrobacter species activity [11]. The results also provide indirect evidence that absolute ammonification is substantial in both forest sites, since the end-product of ammonification is used to feed the nitrification process.

These location attributes are further revealed by calculating relative net nitrification (RNN=(net nitrification)/(net total N mineralization)×100). RNN was least for the grassland site (17%) and for the barren badland site (20%). The native forest site was intermediate with RNN=65%.

RNN for the *Acacia* site was greater than 100% since net ammonification was negative in these afforestation soils. Explicit consideration of the various mineralization traits in future research may contribute to a greater understanding of how *Acacia* afforested sites may alter ecosystem traits due to large soil inorganic nitrogen pools that are easily lost to the environment. Indeed, tree species exert control over nitrate leaching and this important component of ecosystem health should be incorporated into predictions of how nitrate is lost to the environment [12].

The three vegetated sites revealed that total nitrogen in Guam's southern soils is not an effective predictor of the release of available nitrogen for plant growth. The sum of ammonification and nitrification was greatly reduced in the grassland compared with the two forest sites, but total nitrogen was not significantly different among the sites. Use of a direct measure of organic nitrogen may prove to be a more effective proxy for potentially mineralizable nitrogen and predict the potential of these soils to generate available nitrogen more accurately.

Major differences among the three vegetated sites were expected, as genotype of trees can influence local soil properties even in mixed forests [13]. Differences in functional traits of plants may be causal for the species-specific differences that develop following a history of plant soil feedback [14]. Indeed, overlap of plant functional traits does not occur among the three sites comprised of graminoids (savanna), exotic trees with endosymbionts capable of biological nitrogen fixation (*Acacia*), or biodiverse tree community represented by numerous plant families (native forest). Differences between the *Acacia* forest and the native biodiverse forest concur with other reports where non-native tree species have generated soil traits that differ from those of native tree species [15,16].

Paleoenvironmental interpretations differ concerning the origins of savanna grassland in Guam. Disturbance indicators that coincide with signs of human activity were used to interpret that the savanna is anthropogenic and southern Guam was forested prior to human arrival [17]. In contrast, a range of approaches was employed to interpret that natural forces created and sustained the widespread Guam savanna grasslands prior to human arrival [18]. A parallel global debate exists concerning calls for tree-planting to restore lands devoid of tree cover [19] and the need to protect and conserve the world's grasslands and savannas by not planting trees [20]. Use of exotic graminoids that are tolerant of the badland scars to reduce erosion [21] may be more in line with international restoration goals that call for integrity with historical land use during recovery efforts. Caution is warranted especially for converting grassland areas to non-native legume tree species such as *Acacia* [22].

Guam scientists have not effectively attempted to link local conservation management policies and afforestation programs to the broader global agenda. Empirical data such as those reported herein will be required to more fully understand ecological issues influenced by insular conservation management decisions. Since multiple processes acting at multiple scales are the rule rather than the exception in ecology, caution is warranted against the established practice of implementing decisions in the absence of empirical information to quantify all nuances of the impacts of mitigation actions.

Continued local and federal government projects are planned to recover Guam's badlands with *Acacia* plantings. These projects are expensive and do not address the causes for genesis of new badlands. Although the relationship between historical human activities and ancient development of savanna cover and barren scars within savanna is ambiguous, anthropogenic actions are the contemporary means through which new badlands develop and grow. Available funds for badland mitigation may be more effectively spent if they are invested in attempts to modify the human behaviors that create the badlands. This would require a change in approach that includes funding conservation social science research, as advocated elsewhere [23].

Conclusion

Use of non-native *Acacia* trees to recover large badland scars may lead to soil chemical traits that are unique. Watershed management decisions that convert previous coastal grasslands to exotic tree forests may have long-term effects on soil nutrients and modify soil nutrient budgets. Increased knowledge of these ecological processes is needed to enable evidence-informed management decisions and more effectively conserve Guam's coastal ecosystems.

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