PACIFIC COOPERATIVE STUDIES UNIT
UNIVERSITY OF HAWAI`I AT MĀNOA
Dr. David C. Duffy, Unit Leader
Department of Botany
3190 Maile Way, St. John #408
Honolulu, Hawai'i 96822

Technical Report 150

FIRE, EROSION, AND SEDIMENTATION IN THE ASAN-PITI WATERSHED AND WAR IN THE PACIFIC NHP, GUAM

November 2006

Dwayne Minton[1]

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[1] Formerly with the War in the Pacific National Historical Park, Guam, currently U.S. Fish & Wildlife Service, Honolulu.

Fire, Erosion, and Sedimentation in the Asan-Piti Watershed and War in the Pacific NHP, Guam

Report prepared for the National Park Service

Dwayne Minton, Ph.D.
Ecologist
War in the Pacific NHP

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Executive Summary

Erosion and associated sedimentation are one of the primary threats to Guam's terrestrial and aquatic environments. Erosion is will be increased by any activity that reduces vegetation cover. On Guam, anthropogenic fire burns up to 10% of the island's area, mostly in the island's tropical savanna. The complex interactions of fire, vegetation, erosion and sedimentation, while conceptually well understood, have not been investigated on Guam with sufficient detail to inform resource managers.

In the Asan sub-watershed, four fires burned approximately 9% of War in the Pacific NHP between June 2003 and May 2005. In the subsequent wet seasons, erosion from burned savanna was nearly six fold higher than vegetated savanna. This rate was comparable to erosion off badland areas in the same watershed. Even 18 months following a burn, after vegetation had returned to pre-burn levels of biomass, soil loss from burned savanna was twice as high compared to unburned savanna. This was attributed to changes in the species composition of the savanna vegetation community. Fire promoted the spread and establishment of invasive grasses such as *Dicanthium bladhii* and *Pennisetum polystachion*. Both species are capable of altering an area's fire regime by promoting increased fire frequency and intensity. The presence of these species may promote a grass-fire cycle in which the native savanna species (e.g., *Dimeria chloridiformis*) are systematically replaced by fire tolerant invasive grasses.

Erosion was highest is badland areas and recently burned savanna. With burned savanna, timing of rain events appeared important to the overall erosion. Erosion rates on plots burned near the start of the wet season was higher than on plots burned early in the dry season. No differences were observed in the soil loss rates for mixed and fern savanna vegetation subtypes. Erosion rates on swordgrass were not successfully measure in this project.

Sedimentation collection rates were among the highest found in the literature. Sediments showed a distinct pattern associated with point sources. Sedimentation collect also showed distinct seasonal patterns, with sediment collection rates higher in the wet season than the dry. Modeling of the sediment dynamics in the Asan sub-watershed suggested that a sediment flush happened at the start of the wet season. Large storm events were also significant predictors of sediment collection.

Watershed estimates of soil loss showed that badlands and burning near the current rate increase the soil loss by 35% over a habitat without burning and in which badlands are restored to savanna vegetation.

Acknowledgments

A project of this scope could not be completed without the assistance of many people. Ian Lundgren, Holly Tupper, Jenny Drake, and Anna Pakenham of the Resource Management Division of War in the Pacific NHP all provided invaluable support in the field, lab and office. Mr. Eric Brunnemann, Superintendent of War in the Pacific NHP provided invaluable support for this project, without which, this work would not have been completed. Tammy Duchesne and Ali Spittler, both of the National Park Service, and volunteers Elaina Todd, Andrew Bauman, Julie Barr, and Tomas Diego provided valuable assistance with field work. The War in the Pacific NHP Facilities and Maintenance Division, and particularly Mr. Ronald Wilson, Mr. Michael Tajalle, and Mr. Anthony Dodd provided logistic support and assistance with installing erosion flumes. Dr. Mohammad Golabi (University of Guam) was the lead investigator on the erosion flume work discussed in Chapter 5. Clancy Iyekar and Peggy Denney assisted with the installation monitoring of the flumes. Dr. Lynn Raulerson (University of Guam) provided assistance with plant identifications and methodologies to assess savanna conditions. Both Drs. Golabi and Raulerson provided insight through numerous conversations that help to develop of the ideas in this report.

Mr. Dave Limtiaco (Guam Division of Forestry) allowed the erosion flumes to be installed on land under the control of the Department of Agriculture. Fire crews from GFD conducted the controlled burns on the flumes (Chapter 5). Mr. Limtiaco also provided fire statistics for the island and shared his considerable knowledge about the island’s wildfires and their effects on savanna vegetation and erosion.

Mr. Michael Gawel (currently with the Guam EPA), Ms. Vangie Lujan, Mr. Victor Torres of the Guam Bureau of Statistics and planning assisted with obtaining relevant GIS information. Mr. James Byrne (NOAA), Mr. Dave Burdick (Guam Bureau of Planning and Statistics), and Ms. Ifer McCollom (National Park Service) provided considerable GIS technical support.

Mr. Gerry Davis and Trina Lieberer, both of the Guam Division of Aquatic and Wildlife Resources provide space for the PI on their monthly aerial fisherman counts, giving the PI an opportunity to get a different perspective on the Asan sub-watershed.

Dr. Robert Richmond (University of Guam) shared his knowledge about sedimentation impacts on coral reefs. Drs. Larry Basch and Peter Craig, Ms. Sallie Beavers, and Mr. Guy Hughes, all of the National Park Service provided valuable discussion on many aspects of this project.

This project was completed with funding and support from numerous sources. War in the Pacific NHP provided salary for the principle investigator and support staff, laboratory space, supplies, and equipment. The sedimentation work was partially supported by funding from the National Park Service Natural Resource Protection Program Grant for Small Parks (PMIS #89487). Funding for the upland fire and erosion work was obtained from the National Fish and Wildlife Foundation (Project #2001-0336-005), with in-kind nonfederal support from the University of Guam, Guam Bureau of Statistics and Plans, Guam Department of Agricultural, and Micronesian Divers Association. This document serves as the final project report for these funding programs.

Chapter 1.
Overview

Soil erosion and associated nearshore sedimentation are the primary threat to Guam's terrestrial and marine ecosystems (Richmond 1993; Gawel 1999; Birkeland 2000). Soil erosion degrades soil quality, potentially leading to shifts in vegetation composition and declines in productivity (Lal 1995; Giovannini and Lucchesi 1997; Kaihura et al. 1999; Ternan and Neller 1999; Wang et al. 2003). If sufficient degradation occurs, badlands, or areas incapable of supporting vegetation, may result. Streams are adversely affected by sediments, which cause changes in water quality (Neubauer 1981; Townsend et al. 2004) and adversely affect physical habitat. Sediments in the marine environment can smother corals, reduce light availability, and alter water quality (Fabricius 2005), adversely affecting coral survival, reproduction and recruitment.

On Guam, rates of erosion and sedimentation are altered by anthropogenic activities such as burning and poorly managed development, construction and agriculture. Any activity that removes vegetation and/or disturbs land has the potential to increase erosion rates, especially if conducted during the island's wet season (July-December) when rain events are frequent and can be intense.

Intentionally set wildfires are a common occurrence during Guam's dry season (January-June) and denude the ground of soil stabilizing vegetation. Between 1990-98 over 3500 fires burned over 25,000 acres of land in Guam's southern watersheds (CWAP 1998), resulting in erosion that has impacted the terrestrial and aquatic environments as well as human health and standard of living (NRCS 1996; CWAP 1998; NRCS 2001). Illegal wildfires have been identified by the Government of Guam, Department of Agriculture as one the primary threats to Guam's watersheds (CWAP 1998). A 34% increase in erosion in the Ugum watershed on southern Guam has been attributed to illegal anthropogenic burning (NRCS 1996).

Wildfire is a significant driver in the formation and maintenance of savanna ecosystems throughout the world (D'Antonio and Vitousek 1992; van Langevelde et al. 2003). Prior to the arrival of humans, Guam seldom experienced wildland fire due to environmental conditions unfavorable to fire ignition. The introduction of anthropogenic fire has lead to the expansion of savanna vegetation (Athens and Ward 2004) and may be aiding the spread of invasive species, particular grasses that are tolerant of and promote further burning. The presence of savanna vegetation instead of forest may also be contributing to elevated soil loss, as erosion in savanna areas may be 100x times higher than in scrub forest (NRCS 2001).

The complex interaction of fire, vegetation, erosion and sedimentation has been poorly investigated on Guam and must be better understood to improve watershed management. With limited funding, resource managers need sufficiently detailed information to better target management actions that will achieve the largest environmental result. This report describes research conducted by the National Park Service and its cooperators with following objectives:

1. Develop/obtain accurate land use/habitat maps (GIS) for target watersheds and associated coral reef environments.
2. Quantify coastal sedimentation and estimate the potential "zone of impact" on

the reef from the discharged sediments in the target watersheds.

3. Examine effects of fire on savanna vegetation and document shifts in savanna community structure associated with fire, with a special focus on subsequent successional changes and non-native invasive weeds that may be more conducive to burning.
4. Measure erosion by savanna vegetation subtype (included unvegetated badlands) and in burned vs. unburned savanna.
5. Investigate the efficacy of using anti-erosion plants such as vetiver grass (*Vetiveria zizanioides*) to reduce soil erosion and improve soil quality.
6. Develop Best Management Practices (BMPs) to reduce upland erosion and coastal sedimentation.

This study was conducted in the Asan-Piti watershed, located along the western coast of southern-central Guam (Figure 1-1). The watershed contains 1,629 hectares of primarily undeveloped land, comprised of scrub forest, savanna, wetlands, and badlands. Two villages, Asan (2,090 people) and Piti (1,666 people) are situated on the coastal plain, with considerable coastal development, including the island's primary road, Marine Corps Drive (Route 1). A significant amount of development has also occurred on the ridgeline at the top of the watershed, including the construction of military housing, a school, fire department and civilian residential subdivisions. A low ridgeline divides the Asan-Piti watershed in two sub-watersheds, the Asan (1,171 hectares) and the Piti (458 hectares) sub-watersheds. The Asan sub-watershed was the focus of the work discussed in this report.

War in the Pacific National Historical Park is situated within the Asan sub-watershed and conserves approximately 400 hectares of land and water. The National Park was established in 1978 to commemorate the bravery and sacrifice of those who fought in the Pacific Theater of World War II and to conserve examples of the natural resources of Guam. In 2001, War in the Pacific NHP developed a Natural Resource Management Division to better meet its natural resource objectives. This work described in this report was undertaken by the National Park Service to address the War in the Pacific's more serious natural resource impact.

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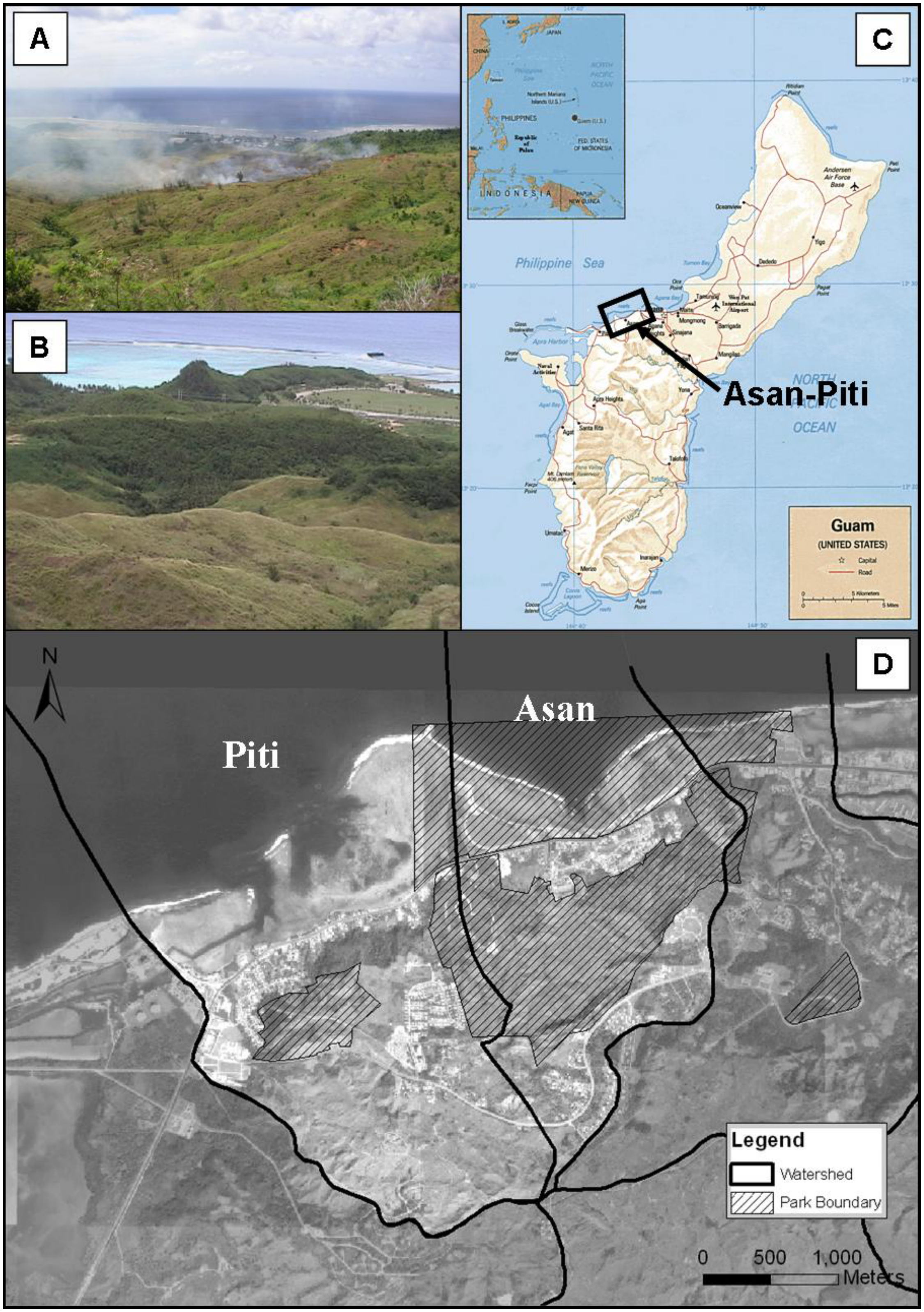

Figure 1-1. The Asan-Piti Watershed and War in the Pacific NHP: a) a fire burns through Asan's savanna on May 16 2004; b) Asan typical vegetation, including savanna (foreground) and scrub forest (back ground); c) the island of Guam; d) the Asan-Piti watershed.

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Chapter 2.
Sedimentation

Introduction

On Guam, sedimentation resulting from poor land management is the single greatest anthropogenic impact to coastal reefs (Gawel 1999; Birkeland et al. 2000). Over the last 25 years, increases in population and changes in land practices have led to significant increases in terrestrial runoff (NRCS 1996), and associated declines in coral abundance, cover, and recruitment (Richmond 1994; 1995; Wolanski et al. 2003a).

Sediments can bury adult and juvenile corals (Rogers 1990; Richmond 1994), impair reproduction (Richmond 1993, 1997), and locally reduce recruitment rates (Hodgson 1990; Gilmour 1999) and juvenile survival (Richmond 1997). While sediment impacts may not always be lethal, coral reef decline may be subtly linked to sediment runoff from adjacent watersheds when sub-lethal affects impair the coral's ability to recover from acute shock, such as tropical cyclones or crown-of-thrown outbreaks (Wolanski et al. 2003b; Fabricius 2005 and references therein).

Sediment can impact coral reef ecosystems through a variety of mechanisms, both direct and indirect (Fabricius 2005 and references therein). Sediments can bury coral (sedimentation or siltation), lower light availability by increasing turbidity, introduce particular organic matter or dissolved nutrients. While all affect coral reef ecosystems, sedimentation affects are believed to have the largest negative impacts relative to the other mechanisms (Fabricius 2005).

War in the Pacific National Historical Park manages 180 hectares of coral reef in the Asan sub-watershed. The coastal edge of the sub-watershed is well developed, containing a small village with a population of approximately 2000 people (US Census Bureau 2001) Inland, the watershed is protected by its inclusion within the National Park, but is still impacted by frequent wildland fires, off-road vehicles, and development along its boundary, all of which contribute to increased soil erosion (NPS, unpub. data). Sediment plumes on the Asan reef are a frequent sight following even modest rain events.

Site-specific information on sedimentation is needed by resource managers, and particularly the National Park Service, to assess the magnitude and characteristics of this potentially serious impact to the marine natural resource of Asan. This information is also critical to the island's growing body of evidence documenting potentially deleterious sediment conditions on Guam's reefs. This project examined spatial and temporal patterns of sediment collection rates on Asan's fore reef. Additional, this project determined basic sediment characteristics to provide insight on the origin and magnitude of the threat to Asan's reefs.

Materials and Methods

Sediment collectors (Figure 2-1a), consisting of three PVC tubes 5 cm in diameter by 13 cm long, were installed 50 cm off the bottom at 25 sites along the fore reef of the Asan Beach Unit of War in the Pacific NHP (Figure 2-1c). Trap dimension were based

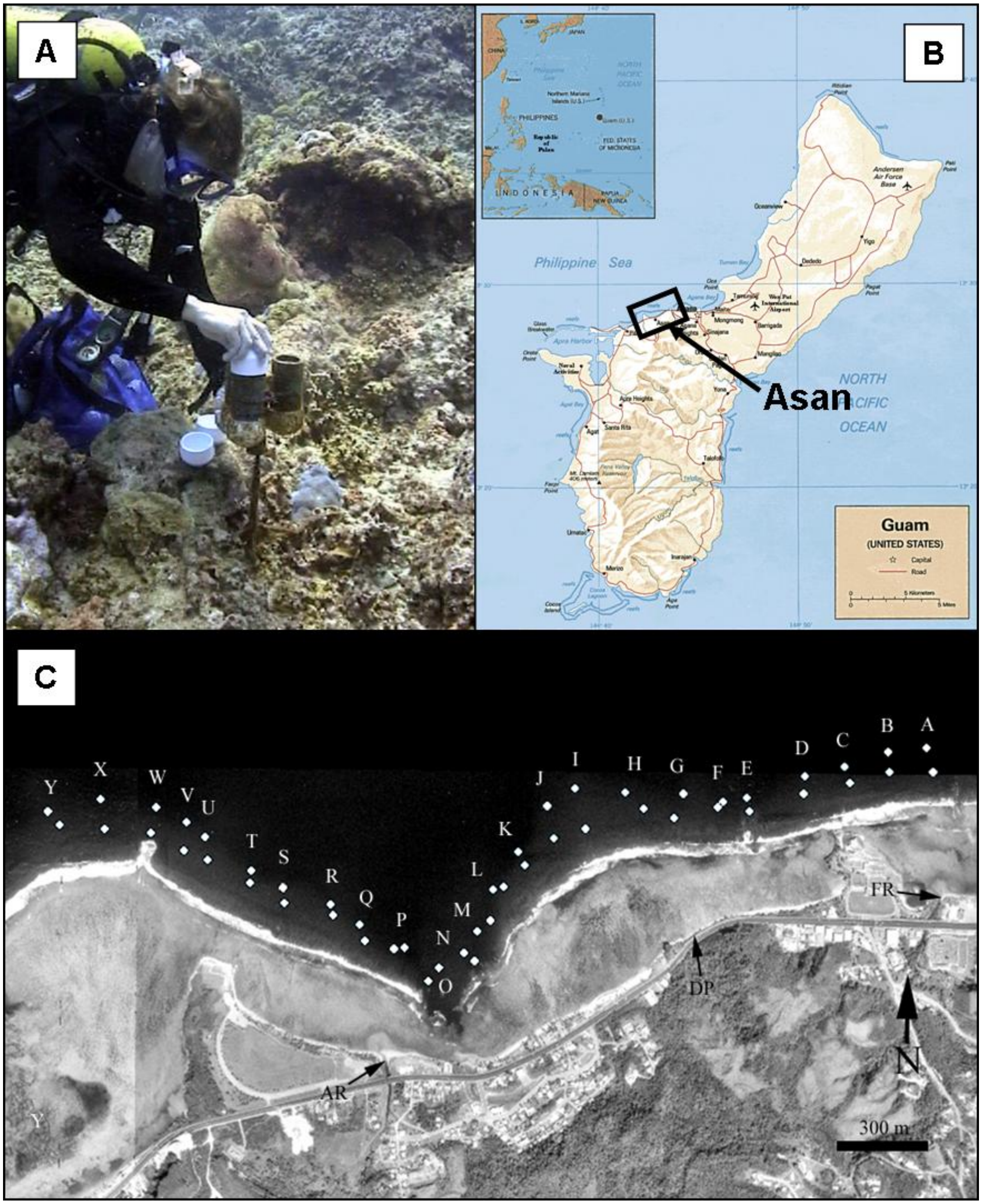

Figure 2-1. a) A diver caps a sediment collector prior to removal; b) The Territory of Guam; c) Sediment Study Sites along the fore reef of Asan Bay. AR=Asan River, DP=Drainage Pipe, FR=Fonte River.

on recommendations of Gardner (1980) and English et al. (1997) to avoid over and under-sampling. At each study site, two collectors were installed, one each at 10 and 20 meter depth. Sites were spaced approximately 150 meters apart. After three weeks, collectors were capped *in situ*, collected by scuba divers, and returned to the laboratory for further processing. New collectors were deployed simultaneously. Seventeen temporal replicates were run between 15 September 2003 and 18 November 2004.

Sediments from two of the three tubes were filtered using pre-weighed Whatman grade 2 papers, dried for 24 hours at 100 ºC in a muffle furnace (Thermolyne F62700), and weighed. Daily sediment collection rates in $g/cm^2/day$ were calculated by dividing gross sediment weights by the surface area of the tube opening and the total number of days left in situ.

Approximately 1 g of sediment was sub-sampled and burned in porcelain crucibles at 550 ºC and 1000 ºC for 1 hour each to determine percent of organic and non-$CaCO_3$ material in the samples. Non-$CaCO_3$ material in marine sediments can be used as a measure of terrestrial input on coral reefs where marine sediments are almost exclusively $CaCO_3$. Upland soils in the Asan Watershed are primarily basaltic in origin, but with some limestone (Young 1988); the percentage of non-$CaCO_3$ material in our samples underestimates the contribution of terrestrial material to the sediments on park reefs. Percent of total was computed for organic material and for non-$CaCO_3$ (e.g. terrestrial) material.

Sediments from the third tube were used to determine grain size. All sediments from the tube were transferred to a 1 liter plastic bottle and allowed to settle for at least 24 hours. Water was decanted from the top of the sediments. To remove organics, a 35% solution of peroxide (H_2O_2) was added until a layer approximately 1 cm thick covered the sediments. Peroxide was allowed to react until all bubbling ceased and a subsequent addition of small amount more of peroxide produced no reaction. To each bottle 2.5 g of sodium hexametaphosphate (SHMP) was added. The bottles were filled to the 500 mL mark and shaken to dissolve SHMP. SHMP was used to prevent clumping. Samples were allowed to stand at least overnight.

Sediments were sorting into four size categories using geological sieves: gravel (#10 mesh), coarse sand (#60 mesh), fine sand (#230 mesh) and silt (pan). Silt were any sediments that passed through the #230 sieve. Prior to rinsing through the sieve, bottles were shaken for at least two minutes. Sediments were washed with a 0.5% SHMP solution until the rinse solution passed clear through the sieves. The silt was transferred to a 1000 mL beaker. Sediments in the sieves were rinsed onto pre-weighed filter papers (Whatman, Grade 2) with distilled water and dried at 100 ºC for 24 hours.

Silt was further processed by filling the beaker to the 1000 mL mark with 0.5% SHMP solution. The beaker was stirred vigorously with a spatula to suspend the silt and a 200 mL sub-sample was removed from the beaker and passed through a pre-weighed filer paper (Whatman, Grade 2) and dried at 100 ºC for 24 hours. Silt was rinsed with distilled water prior to drying.

Daily rainfall data was obtained from the National Weather Service at Tiyan, Guam. Distances from the nearest point source were measured for each sediment collector in ArcGIS using a straight line extending from the center of the river mouth or drainage pipe to the location of each sediment collector.

Sediment weight data were analyzed using a reduced general linear model with terms for time (replicate), location, and depth. Missing samples in some replicates precluded a full model analysis, and the interaction terms could not be included and were assumed to be non-significant. Model fit was examined by examining at residuals. Pearson correlation coefficients were used to examine spatial relationships within the data.

Percent organic, percent terrestrial material, and percent silt were examined using ANOVA with site, depth, and season (wet or dry) as explanatory variables. Fines other grain size data was not statistically examined because of data independence issues, and fines were considered to be the most biologically relevant grain size. Data were arc-sin transformed prior to analysis. Model fit was examined by examining at residuals. A prior multiple comparisons were conducted with Tukey's adjustment to insure an overall $\alpha=0.05$.

All means are expressed as mean ± standard error of the mean, unless specified otherwise. The Minitab statistical package was used for all analyses.

Results

Sediment collection rate (Figure 2-2) showed a significant spatial pattern (ANOVA; F=10.78; df=24,606; $p<0.001$). Sediments downstream of the Asan River (sites L-O) and near Adelup Point (sites A-D) all have elevated sediment collection rates. The 20-meter collectors at site O had the highest average collection rate, 2.302 ± 2.389 g/cm^2/day. The lowest sediment collections rates were observed upstream of Asan River (sites S-Y). The 20-meter collectors at Site W had the lowest average collection rate,

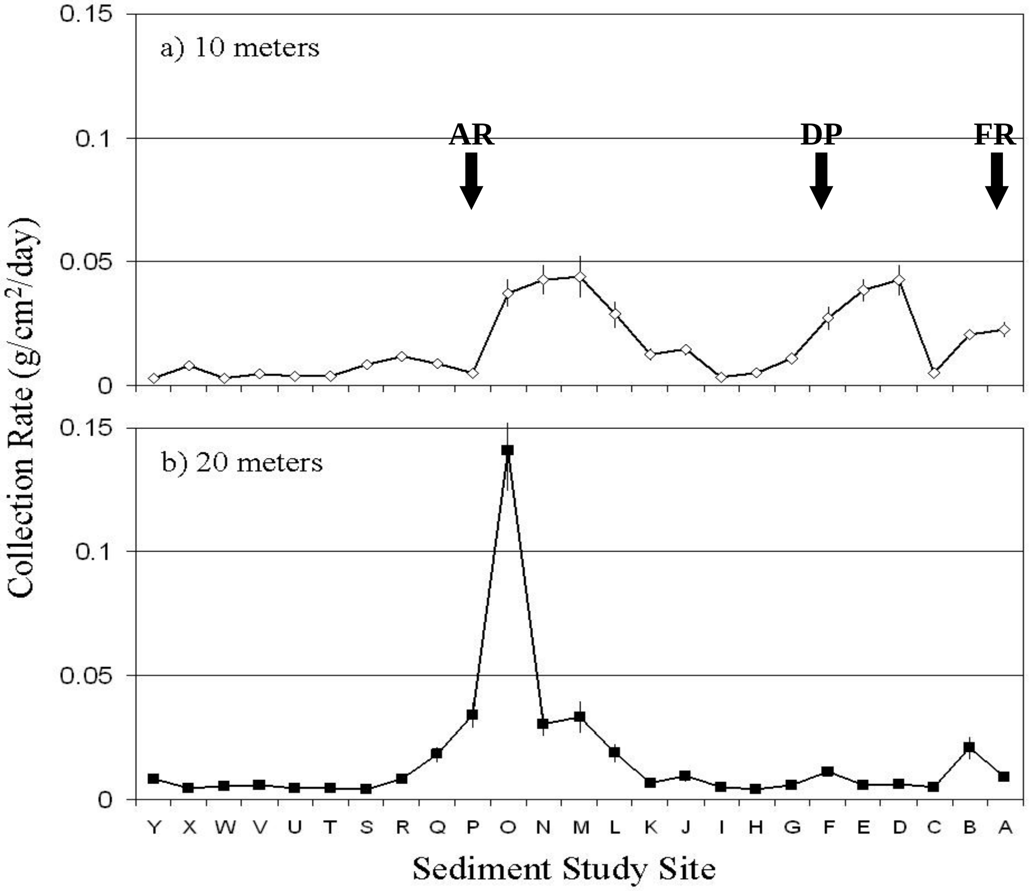

Figure 2-2. Mean (error bars = ±1 standard error) sediment collection rates (g/cm2/day) at a) 10 meter deep sediment study sites and b) 20 meter sediment study sites in Asan Bay. Site reference letters correspond with site locations in Figure 2-1. Arrows represent the approximate location of three sediment point sources.

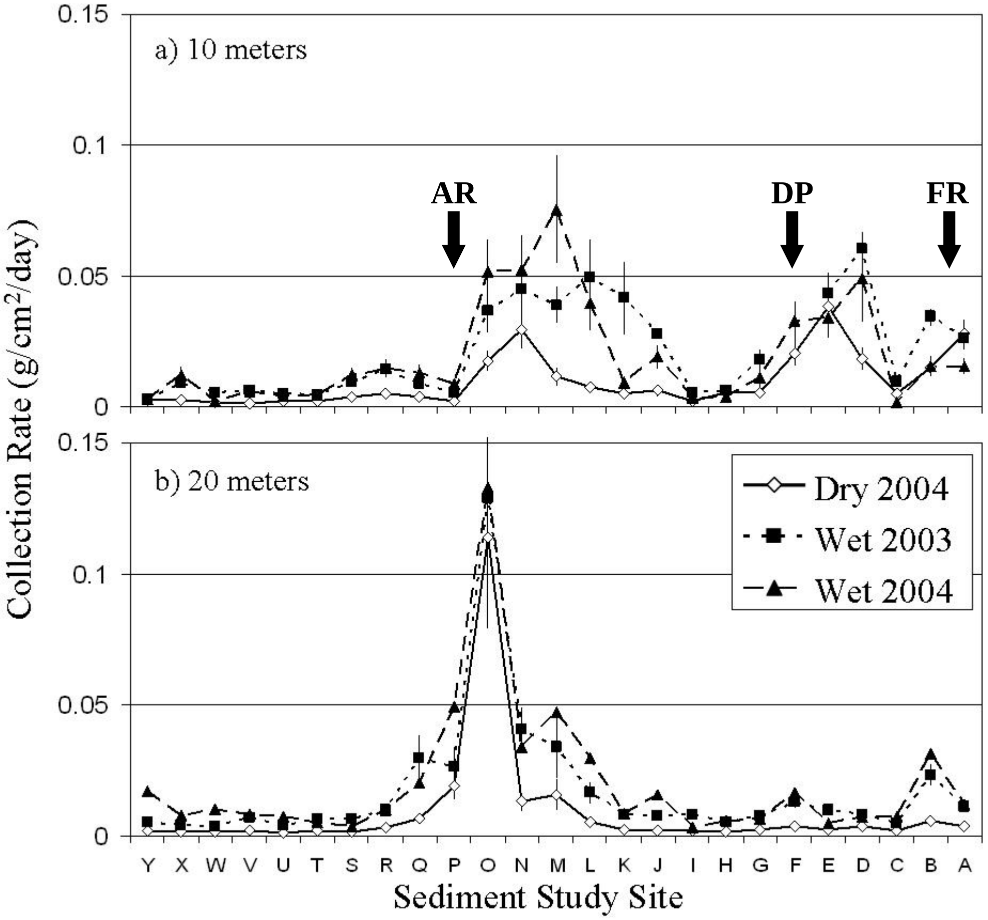

Figure 2-3. Mean (error bars = ±1 standard error) sediment collection rates (g/cm^2/day) by season at a) 10 meter deep sediment study sites and b) 20 meter sediment study sites in Asan Bay. Site reference letters correspond with site locations in Figure 2-1. Arrows represent the approximate location of three sediment point sources.

0.045 ± 0.031 g/cm^2/day. No significant difference in collection rate was found between 10 and 20-meter traps (ANOVA; F=2.32; df=1,606; p=0.128).

Sites with high sediment loads were adjacent to sediment point sources (Figure 2-2). The Asan River drains just west of the Asan Cut; an intermittent storm drainage pipe empties into park waters inshore of site G; and the Fonte River enters just east of Adelup Point, inshore from site A (Figure 2-1). Sediment collection rates declined significantly with distance downstream from a sediment point source (Pearson Correlation; r=-0.304, p<0.001)

Sediment collection rates varied significantly with time (ANOVA; F=16.38; df=16,606; p<0.001). Guam has pronounced wet (July-December) and dry (January-June) seasons, and the average daily rainfall for the replicates collected during the 2004 dry season (0.400 ± 0.043 cm/day) was approximately one third of that for replicates collected during the 2003 (1.145 ± 0.115 cm/day) and 2004 (1.520 ± 0.405 cm/day) wet seasons. Sediment collection rates during the 2004 dry season (Figure 2-3) were approximately half those observed during the 2003 and 2004 wet season; 0.175 ± 0.036 g/cm^2/day compared to 0.364 ± 0.051 and 0.380 ± 0.037 g/cm^2/day, respectively (ANOVA; F=8.92; df=2,620; p<0.001).

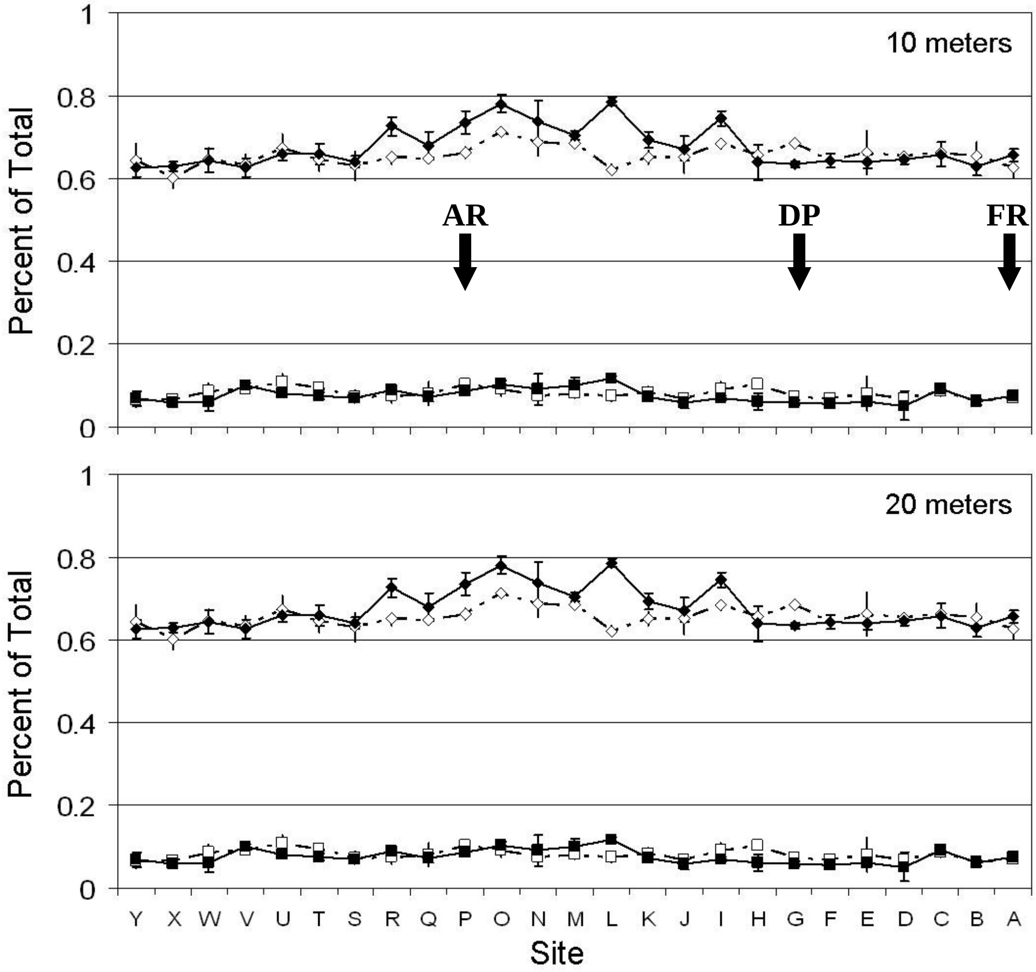

Figure 2-4. Mean (error bars = ±1 standard error) percent of non-CaCO3 (diamonds) and organics (squares) in collected sediments during the wet (solid symbols) and dry (open symbols) season. Sites correspond to those in Figure 1-2. Arrows represent the approximate location of three sediment point sources.

Collected sediments had a high percentage of terrestrial material, varying from a low of 61.9% ± 1.8% at site X-10 to a high of 76.4% ± 2.4% at I-20. The percent of terrestrial material in sediments varied significantly through space (ANOVA; F=4.78; df=24,621; $p<0.001$) and by season (ANOVA; F=7.14; df=1,621; p=0.008), but not with depth (ANOVA; F=0.99; df=1,621; p=0.32). A significant site by season interaction term (ANOVA; F=1.89; df=24,621; p=0.007) was also observed. In general, sediments collected from near Asan Cut (Sites M-P) had significantly higher percent of terrestrial material in the sediment than sites away from the cut (Figure 2-4). During the wet season, sites around Asan Cut showed a higher percent of terrestrial material compared to sites away from the cut, where little difference was observed (Figure 2-4).

Organic material in the collected sediments varied from 3.9% ± 3.5% at site A-10 to 16.9% ± 5.2% at site D-20. Percent organic material in sediments (Figure 1-5) did not significantly vary with site (ANOVA; F=1.17; df=24,619; p=0.267), season (ANOVA;

F=3.17; df=1,619; p=0.076) or depth (ANOVA; F=0.54; df=24,619; p=0.463). The site by depth interaction term was significant (ANOVA; F=1.81; df=24,619; p=0.011), but an examination of an interaction plot suggests it had little affect the overall results of the analysis.

Small grain sizes were the predominant component of the collected sediments (Figure 2-5). Sediment size #230 was the largest fraction by weight, comprising 37.5% ± 0.5% of the samples. Fines were the next largest component, forming, on average, 29.9% ± 0.8% of the sediments. Grain sizes larger than #10 were only 6.1% ± 0.5% of the total weight of the samples. Deep sites (20 meters) had a significantly greater percentage of fines than shallow sites (ANOVA; F=8.41; df=24,349; p=0.004), 32.8% ± 1.2% versus 26.8% ± 1.2%. The wet season also had significantly higher percentage of fines than the dry season (ANOVA; F=11.31; df=24,349; p=0.001). The wet season averaged 31.9% ± 1.0% compared to 26.6% ± 1.2% for the dry season. Fines did not vary by site (ANOVA; F=0.96; df=24,349; p=0.519). The ANOVA model had no significant interaction terms.

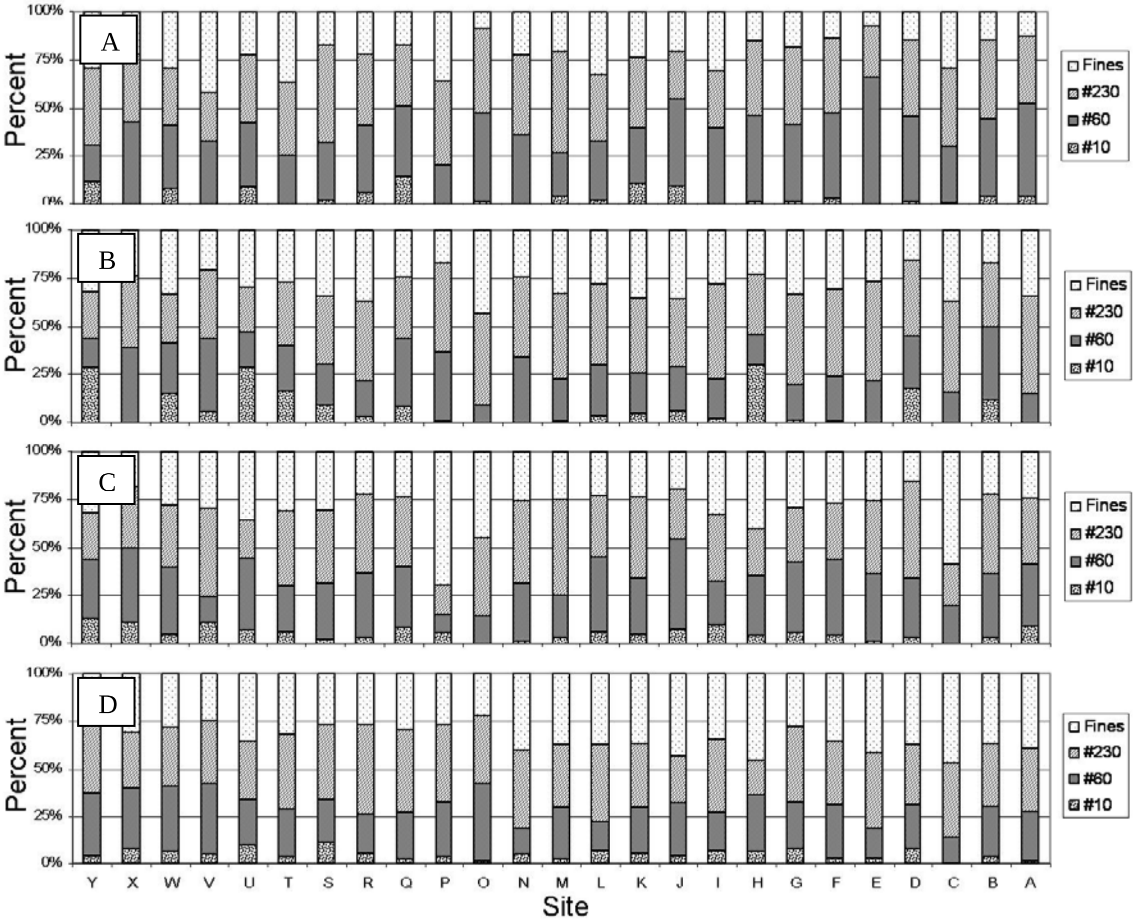

Figure 2-5. Mean percent of total for four grain size categories: a) 10 meter samples during the dry season; b) 10 meter samples during the wet season; c) 20 meter samples during the dry season; and d) 20 meter samples during the wet season. Sites correspond to those in Figure 2-1.

Discussion

The deleterious effects of sedimentation on coral reef ecosystems have been well documented in the literature (Table 2, Fabricius 2005). Elevated sediments can reduce calcification rates (Tomascik and Sander 1985; Abdel-Salam et al. 1988; Rogers 1990), affect energetics (Abdel-Salam et al. 1988; Telesnicki and Goldberg 1995; Philipp and Fabricius 2003), reduce reproduction (Richmond 1994; Gilmour 1999) and recruitment (Richmond 1997; Babcock and Smith 2002), and lower adult survival (Riegl and Branch 1995; Wessling et al. 2001).

Both the length of exposure and the magnitude of the sediment event contribute to the degree of degradation (Rogers 1990; Fabricius and Wolanski 2000). Chronic, small events can be as deleterious to coral survival as large periodic events (Philipp and Fabricius 2003). After reviewing numerous sedimentation studies, Rogers (1990) concluded that sediment collection rates over 0.01 g/cm^2/day were sufficient to cause negative impacts on corals. Pastorak and Bilyard (1985), based on sedimentation data collected on Guam by Randall and Birkeland (1978), predicted severe to catastrophic impacts to coral reefs at chronic sedimentation rates >0.05 g/cm^2/day. Sedimentation rates greater than 0.1 g/cm^2 have been shown to kill exposed coral tissue with a few days (Riegl and Branch 1995).

The sediment collection rates measured in this study are among the highest reported in the literature (Rogers 1990; Fabricius 2005 and references therein). Numerous studies conducted on the Great Barrier Reef using comparable methods (Mapstone et al. 1989; Hopley et al. 1990) found sediment collection rates 1-3 orders of magnitude less than the peak rates observed on the Asan fore reef. Rates reported from the Caribbean tend to be even lower than those reported for the Great Barrier Reef (Hopley et al. 1990; Rogers 1990 and references therein; Nogues and Roberts 2003). The extremely elevated rate of sediment collection is sufficient to raise serious concerns about the long term health and survival of Guam’s reefs (Richmond 1997).

Over 60% of the collected sediment was comprised of non-$CaCO_3$ material, suggesting a terrestrial origin. This estimate of the terrestrial sediment component is low, considering limestone is a significant component of the terrestrial soils in the Asan sub-watershed (Young 1988). Over the last 25 years, upland erosion and coastal sedimentation rates on Guam are believed to have increased as a result of population growth and poor land management practices (NRCS1996; Gawel 1999). In the Asan sub-watershed, inadequate enforcement of environmental regulations, poor erosion control associated with development, and wildland arson all contribute to increased soil erosion and subsequent sedimentation on nearshore coral reefs.

Even given the extremely high rate of sediment collection, the reefs of Asan are not buried in mud. The presence of living corals suggests that much of the sediment is being removed from the system buy periodic storms or consistent oceanographic conditions. Typhoons are frequent events on Guam and play a significant role in removing accumulated sediments from another Guam watershed (Wolanski et al. 2003a). The presence of seasonally high wave energy and periodic large storms may be sufficient to flush sediments from the Asan reef. However, high turbidity from suspended fine sediments is common on the Asan fore reef (Minton, pers. obs.) and may be significantly impacting coral survival, reproduction and recruitment. Adult corals often show signs of stress (Minton, pers. obs.), and low coral recruitment along the Asan fore reef may be linked to sediment accumulation on the bottom or reduced light availability resulting from suspended sediments (Lundgren and Minton 2005).

Sediment collection rates were correlated with distance downstream from the nearest point source. Point source, as opposed to non-point source runoff, appears to be the primary avenue for sediment transport from the Asan watershed onto the adjacent reef. While no significant difference in sediment collection rate was found between 10- and 20-meter collectors, plume effects were more evident in shallow water, suggesting influxing sediments were moving parallel to the reef crest and not being transported immediately offshore. After some rain events, sediment plumes 2-3 meters thick were observed floating on the ocean surface and moving parallel to the reef crest. Similar plumes have been documented at Fouha Bay on southern Guam (Wolanski et al. 2003a).

Sediment composition also plays a significant role in the amount of damage caused to coral tissues (Fabricius 2005). Coral damage increases with increasing organic content and with decreasing grain size (Hodgson 1990; Weber et al. 2004). While little variation was observed in organic content, the percentage of fines in sediments significantly increased with depth and by season. Ocean conditions in Asan are at their calmest during the rainy season, when sediment inputs are elevated (Figure 1-5.) and a greater proportion of terrestrial derived clays are washed into the nearshore waters, potentially accounting for the increase in the percentage of fines in collected sediment. With reduced wave energy at deeper sites, smaller particles would readily settle onto the benthos.

Healthy coral reefs have been observed in nearshore areas where sediment inputs are common, suggesting that these reefs may be adapted to intense sediment regimes (Ayling and Ayling 1998). Coral communities may also be able to adapt to chronic, elevated sediment conditions, allowing them to survive in areas receiving consistent but elevated sediment inputs (e.g. river mouths). In Asan, corals surviving at sites receiving the highest sediment loads tend to have massive growth forms (Minton, pers. obs.). This growth form generally displays a higher tolerance to elevated sedimentation rates compared to smaller forms (Rogers 1990). However, the true health of these corals is uncertain, and sediment effects my act in a sub-lethal manner, impairing successful reproduction and recruitment. On Guam, the peak coral spawning and larval settlement occurs during the wet season (Richmond and Hunter 1990), when sediments are at their highest and oceanographic conditions are the poorest for sediment flushing. Early life history stages and processes (e.g. larval survival and settlement) are adversely affected by significantly lower sediment inputs than adult corals (Hodgson 1990; Gilmour 1999), raising concerns that while adult corals are surviving on Asan’s reef, they are not being adequately replaced by new individuals. These findings raise serious concerns for the future health of Asan’s coral reefs.

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Chapter 3.
Savanna Vegetation and Fire

Introduction

Wildfires are a significant ecological driver in savanna and grassland communities (D'Antonio and Vitousek 1992; van Langevelde et al. 2003), and, while no single event can completely explain savanna-grassland dynamics (Scholes and Archer 1997), fire has been shown to play an important role in the formation, maintenance, and function of these ecosystems (D'Antonio and Vitousek 1992 and references therein; Higgins et al. 2000; van Langevelde et al. 2003). Numerous studies worldwide have demonstrated the significant role of fire in the savanna ecosystem, including Africa (Higgins et al 2000; van Langevelde et al. 2003), the Americas (Streng and Harcomber; Hoffman 1999), Australia (Gill 1999) and Oceania (Hughes et al. 1991; Friefelder and Vitousek 1998; D'Antonio et al. 2000).

Relative to other plants, grasses have a high surface area:volume ratio of leaves and typically accumulate large amounts of dead, above ground biomass, features that increase the probability of ignition and create conditions suitable to sustain and spread fire (Mack and D'Antonio 1998). Many grasses possess life history traits that are fire adapted (Smith and Knapp 2001) including the ability to readily and quickly re-sprout from root masses following burning, quick growth, high light saturation points, and ample seed production. However, generalizations among grass species are difficult, and changes in grass species composition can significantly alter fire regimes (D'Antonio and Vitousek 1992; Mack and D'Antonio 1998; Grace et al. 2001; Rosssiter et al. 2003), leading to long-term changes in savanna composition (Woube 1998; Rossiter et al. 2003).

Currently, savanna communities comprise approximately 1/3 of Guam's vegetated area (Donnagan et al. 2002). Prior to human arrival, savanna grasslands are believed to have been rare on the island (Raulerson 1979), but the application of human derive fire starting anywhere from 3,500-4,300 years ago (ya), as evidenced by charcoal deposits in the paleographic record (Athens and Ward 2004), contributed to their expansion. Charcoal increase around 2,900 ya suggest fire became more prevalent on the Guam, and by 2,300 ya, most of Guam's southern forest may have been replaced by savannas (Athens and Ward 2004).

Prior to human arrival, natural fire is believed to have been rare on the island. The moist tropical climate and the island geological composition are not conducive to a natural fire regime. High humidity makes spontaneous ignitions improbable. Other fire sources are either absent or rare. Lava is not present and cloud to ground lightning is rare. When it does occur, cloud to ground lightning is usually accompanied by heavy rain, reducing the likelihood of vegetation ignition.

Guam's savannas are a xeric ecosystem characterized by a relatively continuous grass layer intermixed with solitary trees and bushes and bare patches of exposed saprolite clay (Raulerson 1979). Savannas tend to inhabit acidic volcanic soils common in southern Guam and in the Asan sub-watershed (Young 1988). However, wetland, and limestone species can also be found in the savanna, but are relatively rare in the Asan sub-watershed. Stone (1970) recognized four subtype communities in the savanna: 1) *Miscanthus*, 2) *Dimeria*, 3) erosion scar, and 4) *Phragmites*.

The *Miscanthus* or “swordgrass” subtype is dominated by the native bunchgrass grass *Miscanthus floridulus*, which often grows in dense monotypic stands on steeper slopes and in burned areas. *Miscanthus* is capable of surviving low intensity fire (Raulerson 1979) and readily re-sprouts from its dense root mass (Minton pers. obs.). The species is able to grow in excess of 3m in height.

The *Dimeria* or “mixed” subtype is believed to be the native climax savanna community (Fosberg 1960). While numerous species are present in the mixed community, the native grass *Dimeria chloridiformis* tends to dominate. The species in this community appear to be fire intolerant (Raulerson 1979), and if burned are replaced by *Miscanthus*. A variety of native forbes and shrubs are also common in this subtype, including *Stachytarpheta jamaicensis* and *Centosteca lappacea*.

The erosion scar or “fern” subtype is found in patches of nutrient poor bauxite clays. These soils are common along the edges of erosion scars and may eventually colonize the scars themselves. The fern *Dicranopteris linearis* is the dominant species, but a variety of grasses, shrubs and trees ay also be present. Many of these are considered to be pioneer species.

The *Phragmites* subtype is often found in valleys in areas of marshy ground. Raulerson (1979) considers Stone’s (1970) subtype to be a category of riverine forest and instead describes this savanna subtype as one that can include *Phragmites karka*, but also may be dominated by a variety of sedges. As this community seldom burns, it will not be discussed in further detail in this report.

The role of fire in shaping Guam’s savanna communities is poorly understood. Guam’s native savanna plants evolved in an environment devoid of natural fire, and probably persisted in regions where soil and/or environmental conditions could not support native forests. While savannas have probably expanded as a direct result of anthropogenic burning, Guam’s savanna species may be poorly adapted to high fire frequency or intensity. Invasive grass species are present in the island’s savannas (Stone 1970, Raulerson 1979), but their distribution and ecological effects are poorly understood. Their potential role in altering island fire regimes could create significant adverse affects on the native community. This chapter will examine the extent of burning on Guam and its impact on the savanna vegetation of the Asan sub-watershed and the Asan inland Unit of War in the Pacific NHP.

Materials and Methods

Fire

Fire history for Guam was obtained from the Guam Department of Agriculture, Division of Forestry. Weather data were obtained from the Tiyan Guam office of the National Weather Service. Seasonal variation in Guam’s weather, and particularly in its rainfall, is influenced by shifts in the monsoon trough and a latitudinal shift in subtropical high pressure zones (Guard et al. 1999). Annual variability in rainfall is also linked to the periodic oscillation in El Nino Southern Oscillation (ENSO). ENSO events occur on average at four-year intervals, but intervals can vary between two and ten years. Strong ENSO events can result in extended drought conditions the following year (Lander and Guard 2003), which create ideal conditions for increased fire frequency and intensity.

Data on ENSO events was obtained online from the Center for Oceanic-Atmospheric Prediction Studies (COAPS)

Starting in June 2002, all fires occurring in War in the Pacific NHP were field mapped by walking the burn's perimeter with a Trimble CE GPS unit within 72 hours of the fire. Data were converted to GIS layers in ArcGIS to compute fire size (in hectares).

Vegetation

At the start of this research, no vegetation habitat maps were available for the Asan Inland Unit of War in the Pacific NHP. To select sites, 200 random points were generated using ArcGIS and overlain on 2002 IKONOS imagery. Any points that occurred in forested vegetation were excluded from further analysis and all remaining points were field investigated to determine savanna habitat type and slope. Vegetation cover was visually estimated as percent coverage of swordgrass (*Miscanthus*), fern (*Dicranopteris*), and grass (other than *Miscanthus*). Random points were systematically investigated until four sites with similar slope (between 9 and 12%, as measured with an inclinometer) were obtained for each of the following habitat types:

1. *Dimeria* Community (hereafter "mixed")
2. *Miscanthus* (hereafter "swordgrass")
3. Erosion scar (hereafter "fern")
4. Burned

In June of 2003, four mixed and three burned study plots were established prior to onset of the wet season. Burned plots were established following a June 2003 fire in the Asan Inland Unit of war in the Pacific NHP. Randomly selected sites were investigated until plots meeting the selection criteria were located. Because of the relatively small size of the burn, only three suitable sites were found. Following the wet season, four fern and four swordgrass plots were installed. Because of the dense nature of swordgrass, these plots were never successfully relocated and will not be discussed further in this report.

Each study plot measured 10m x 10m and contained visually homogenous vegetation characteristic of a savanna subtype. Vegetation samples were collected from two 1.5m by 0.75m quadrats randomly positioned along the perimeter of each plot. This method was used to avoid impacting the erosion measurements that were be taken simultaneously (Chapter 4). All vegetation, including above and blow ground biomass was removed from each sampling quadrat and returned to the lab. The vegetation was washed to remove all soil, sorted by plant species and dried for 48 hours at 40°C in a drying oven. Dried material was weighed to the nearest gram using an electronic balance. All biomass data was standardized into grams/m^2. Within each plot, a species checklist was made to capture rare individuals that may not have occurred in the biomass quadrats.

Species number and total biomass were compared using a one-way ANOVA. Cluster analysis using average linkages was performed to examine similarities in species composition among the study plots.

In June of 2003, as part of another aspect of this project, four soil erosion flumes were established along Cross Island Road (Route 17) to study the effects of fire on erosion rates under different treatments (See Chapter 4). A control burn was applied as one treatment. Prior to the control burn on 16 January 2004 and again in Jan 2004 after vegetation had regenerated, two 1.5m by 0.75m plots were sampled and processed for biomass as described above.

In 2004, a vegetation map for the island was obtained in a GIS image file. For the Asan-Piti watershed, the image file was converted into a layer using ArcGIS 9.0. Total hectares and percent of watershed for each vegetation type were calculated from the layer file.

Results

Fire

Between 1979-2000, Guam averaged 730 fires/year that burned 1,942 hectares (4,800 acres), or approximately 4% of the island's total area. Fire occurrence was highly variable among years, ranging from a low of 152 ignitions in 1994 to a high of 1,944 fires in 1998.

Geographically, the majority of fires occur in southern Guam (Neill and Rea 2004). This area of the island is less populated and has a higher percentage of suitable habitat for savanna (i.e. volcanic soils). Because it is also a rural area, inhabitants of the southern villages may be more likely to engage in activities such as hunting, where fire is routinely employed to enhance success. Additionally, because of the relative remoteness from Guam's main population and business centers, southern village are patrolled less by law enforcement personnel.

From 1991-2000, the majority of fire ignitions (>95%) occurred during the island's dry season (January to June), with the peak months occurring from March to May (Table 3-1). These months also had the largest average fire size and largest maximum fire size. Annual fire variability was strongly correlated with rainfall, with number of fires (Pearson Correlation; $\rho=-0.82$; $p<0.001$) and size of fires (Pearson

Table 3-1. Total number of fires, mean fire size and maximum fire size by month. Data are for the years 1991-2000).

Month	Mean Rain (mm)	Fires	Mean Size (ha)	Max. Size (ha)
January	3.91	700	1.89 (±0.39)	202.34
February	2.78	991	1.30 (±0.14)	80.94
March	2.88	2022	2.79 (±0.49)	663.68
April	3.46	1917	1.73 (±0.21)	283.28
May	5.66	1276	2.80 (±0.80)	797.23
June	5.93	510	1.22 (±0.20)	80.94
July	9.83	88	1.84 (±0.32)	16.19
August	12.32	6	0.72 (±0.31)	2.02
September	14.04	14	0.14 (±0.08)	1.21
October	11.69	22	0.09 (±0.02)	0.40
November	8.02	40	0.24 (±0.07)	2.02
December	5.27	88	0.91 (±0.20)	12.14

Table 3-2. Mean (±SE) number of fires and hectares burned the year following an ENSO event (After ENSO) and other years (No ENSO).

	After ENSO (n=4)	**No ENSO (n=17)**	**T**	**df**	**p-value**
Number of fires	1360 (±236)	578 (±70)	3.17	3	0.05
Acres burned	4,442 (±319)	1,352 (±294)	7.12	9	0.0001

Correlation; ρ=-0.69; p=0.001) of the fires both negatively correlated with annual rainfall. Years following an ENSO event experienced significantly more fires and larger fires than other years (Table 3-2).

Between June 2003 and April 2005 four fires burned 19.52 hectares, or 1.67% of the Asan sub-watershed (Table 3-3). In total, 4.55% of the sub-watershed's savanna lands burned. All of these fires burned wholly or partially within the boundary of the Asan Inland Unit of War in the Pacific NHP (Figure 3.1) and burned a total 19.18 hectares or 8.7% of the Asan Inland Unit. Fires ranged in size from 0.08-13.3 ha.

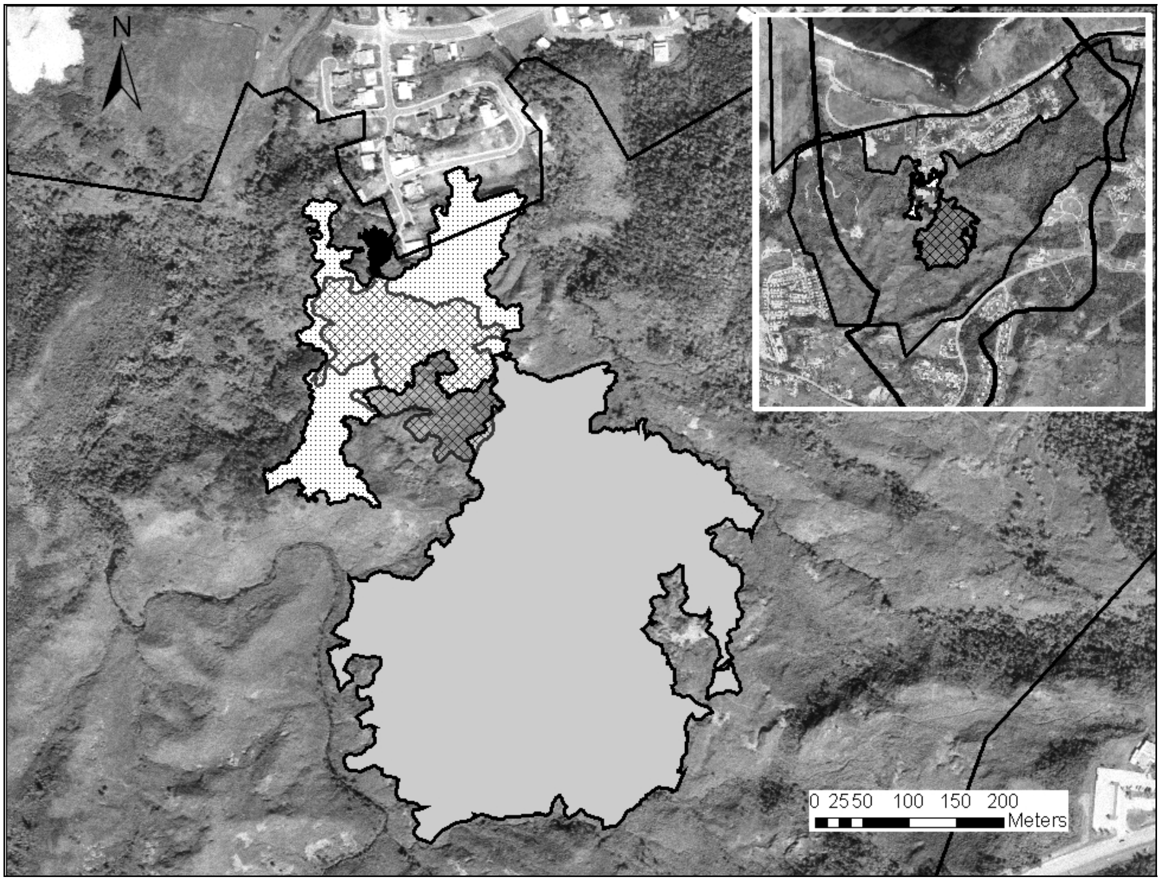

Figure 3-1. Four fires between June 2003 and May 2005 burned 19.52 hectares of the Asan sub-watershed. Inset shows location of the burns within the Asan sub-watershed at a larger scale. Thick line is the watershed boundary; thin line is the boundary of War in the Pacific NHP.

Table 3-3. Hectares of savanna burned between June 2003 and April 2005 in the Asan sub-watershed and the Asan Inland Unit of War in the Pacific NHP.

Fire Date	Total Burned (ha)	Burned in Park[1] (ha)	Percent of Park[1] Burned	Percent of Asan Sub-Watershed Burned
June 2003	2.25	2.25	1.02	0.28
May 16, 2004	13.30	13.30	6.03	1.65
May 30, 2004	0.08	0.08	0.04	0.01
April 31, 2005	3.89	3.55	1.61	0.48
Total	19.52	19.18	8.70	2.42

1Asan inland unit of War in the Pacific NHP (220.4 ha)

Vegetation

Even though two villages and an estimated 3,756 people (Asan: 2,090 people, Piti: 1,666 people) (U.S. Census Bureau 2001) reside in the small Asan-Piti watershed, nearly 75% of the available land, or 612.2 hectares, is undeveloped (Table 3-4). Scrub forest is the dominant vegetation in the watershed, comprising 297.58 hectares (37.0% of the total). The scrub forest is composed primarily of the tree *Leucaena leucocephala* (tangantangan). The watershed has 312.23 hectares of savanna vegetation (38.8% of the total). The vegetation data did not possess sufficient resolution to obtain data on the savanna subtypes. Barren areas and wetland habitats each comprised less than 1% of the watershed, but this estimate is known to be inaccurate based on recent aerial surveys that show barren areas misclassified as savanna in the original GIS vegetation image.

The Asan sub-watershed comprises 362.01 hectares, or 45.0% of the total watershed. Within the Asan sub-watershed, scrub forest is the dominant vegetation type. Savanna vegetation is the second most dominant, covering 105.2 hectares (20.1%) of the sub-watershed. Barren areas account for only 0.27 hectares, or 0.07 percent of the sub-watershed.

All plots showed high variability, and as such no statistically significant differences were found among the three plots for species number (ANOVA; F=2.45; df=2,10; p=0.147) or total biomass (ANOVA; F=0.52; df=2,10; p=0.613). However,

Table 3-4. Vegetation types (in hectares) in the Asan-Piti Watershed and the Asan and Piti sub-watersheds.

	Piti		Asan		Asan-Piti	
	Hectares	Percent	Hectares	Percent	Hectare	Percent
Scrub Forest	127.43	28.83	149.66	41.34	277.09	34.47
Limestone Scrub Forest	9.98	2.26	10.51	2.90	20.49	2.55
Savanna Complex	207.03	46.85	105.20	29.06	312.23	38.84
Barren	0.69	0.16	0.27	0.07	0.96	0.12
Urban	95.37	21.58	96.37	26.62	191.74	23.85
Water	1.43	0.32	0.00	0.00	1.43	0.18
	441.93		362.01		803.94	

burned plots showed a trend toward lower biomass compared to both mixed and fern plots. Species diversity also showed a decreasing trend from mixed>burned>fern (table 3-5).

Vegetation plots varied in their species composition (Table 3-5; Appendix 3). Fern plots were dominated by *Dicranopteris linearis*, which comprised 91.6% of the vegetation cover. Mixed and burned plots showed similarities in species composition but species dominance differed (Table 3-5). Whereas three species (*Dicanthium bladhii*, *Dimeria chloridiformis*, *Pennisetum polystachion*) accounted for 64% of the biomass in mixed plots, *Dicanthium bladhii* tended to dominate burned plots (60%).

The cluster analysis produced three clusters (Figure 3-2). The four fern plots were distinct from both the mixed and burned plots. Mixed-2 clustered alone. The remaining mixed and burned plots clustered together sharing 63% similarity. Burn-1, Burn-3 and Mixed-4 formed a group within cluster three that shared 92% similarity.

Table 3-5. Mean percent (±SE) of total biomass of all species found in vegetation plots.

Species	**Native**	**Mixed (n=4)**	**Burned (n=3)**	**Fern (n=4)**	**Badland (n=3)**
Centosteca lappacea	yes	1.0 (<0.1)	2.81 (2.81)	-	-
Dicanthium bladhii	no	30.85 (17.79)	59.82 (15.38)	-	-
Dimeria chloridiformis	yes	12.86 (10.27)	-	<0.1 (<0.1)	-
Pennisetum polystachion	no	22.30 (16.19)	3.22 (3.22)	0.3 (0.3)	-
POACEAE #1	?	4.02 (3.76)	0.22 (0.15)	-	-
POACEAE #2	?	1.08 (0.70)	-	-	-
CYPERACEAE	?	8.11 (8.11)	20.95 (20.95)	1.7 (1.7)	-
Fimbristylis dichotoma	no	0.13 (0.13)	0.25 (0.25)	-	-
Fimbristylis tristachya	no	6.95 (6.95)	-	-	-
Rhyncospora ruba	no	6.00 (6.00)	-	-	-
Alysicarpus vanginalis	no	0.35 (0.29)	0.04 (0.04)	-	-
Chromalena odorata	?	-	0.05 (0.05)	-	-
Curculigo orchioides	yes	0.02 (0.02)	0.02 (0.02)	-	-
Hyptis capitata	no	1.21 (0.75)	12.51 (10.40)	-	-
Stachytarpheta jamaicensis	yes	4.20 (3.98)	0.12 (0.12)	<0.1 (<0.1)	-
Timonius mollis	yes	-	-	6.1 (6.1)	-
Waltheria indica	yes	0.17 (0.17)	-	-	-
Arudina graminifolia	no	0.79 (0.78)	-	-	-
Cassytha filiformis	no	-	-	<0.1 (<0.1)	-
Dicranopteris linearis	yes	-	-	91.6 (5.8)	-
Lindsaea ensifolia	yes	-	-	0.2 (0.2)	-
Total Biomass(g)/Plot		969.9 (391.6)	591.8 (193.6)	951.1 (134.4)	0.00
Species/Plot		7.3 (1.4)	5.3 (1.3)	2.8 (1.4)	0.00

Vegetation Type	**Mixed**	**Burned**	**Fern**	**Badland**
Native	18.2 (9.4)	3.0 (2.8)	98.0 (2.0)	0.00
Non-native	55.5 (21.7)	75.6 (19.7)	0.3 (0.3)	0.00
Unknown	26.3 (15.1)	21.5 (21.0)	1.7 (1.7)	0.00

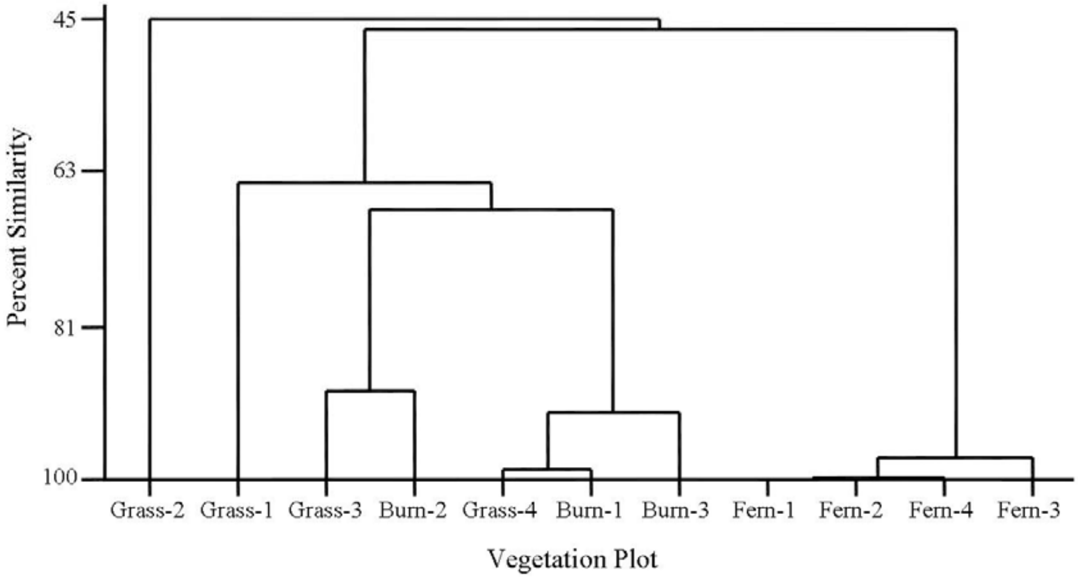

Figure 3-2. Cluster dendrogram for all mixed, burned and fern plots. Cluster analysis was performed on species biomass data for each plot.

Introduced species dominated all plots except fern plots (Figure 3-3). The grasses *Dicanthium bladhii* and *Pennisetum polystachion*, the mint *Hyptis capitata*, and sedges (Including *Fimbristylis tristachya* and *Rhyncospora ruba*) were the most common introduced species. While both mixed and burned plots tended to be dominated exotic species, native species comprised only 3% of the biomass of the burned plots. (Figure 3-3) compared to 18.2% observed in mixed plots. Because of the small sample size and high variability within plot types, no statistically significant differences were observed among the plot types.

In the flume experiment, the vegetation composition change in the treatment plot following the application of the controlled burn. *Dicanthium bladhii* increased from 3.1% to 79.7% of the vegetation. In the control plot, little change in vegetation composition or relative abundance was noted (Figure 3-5).

Discussion

The savannas in the Asan sub-watershed (and most likely on all of Guam) are a complex mosaic of vegetation subtypes undergoing a fire-driven transformation in their species composition. This is particularly evident in mixed savanna, where following burning, the species composition is undergoing change, and exotic species, particularly grasses such as *D. bladhii*, are invading burned areas and inhibiting the re-establishment of non-fire adapted native species (e.g. *Dimeria chloridiformis*). Over a year after the fire, *D. bladhii* is still the dominant species in burned areas (Minton pers. obs.) *Dicanthium bladhii*, a native of Australia and Asia, is fire tolerant and readily regrows after burning (Grace et al. 2001). It is tolerant of drought and acidic (pH 5-5.5) and low fertility soils (NRCS 2002). Growing to a height of 3-4 feet, *D. bladhii* produces sufficient above ground biomass to contribute to fire fuels and this species appear to

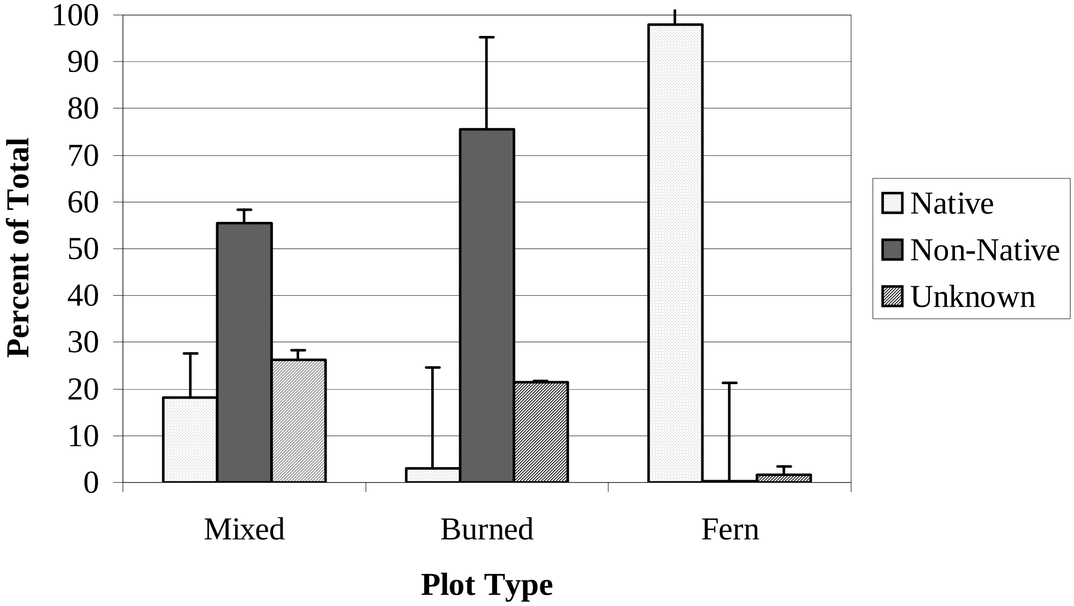

Figure 3-3. Mean percent of total biomass comprising native, non-native and unknown plants vegetation plots. Error bars are standard errors.

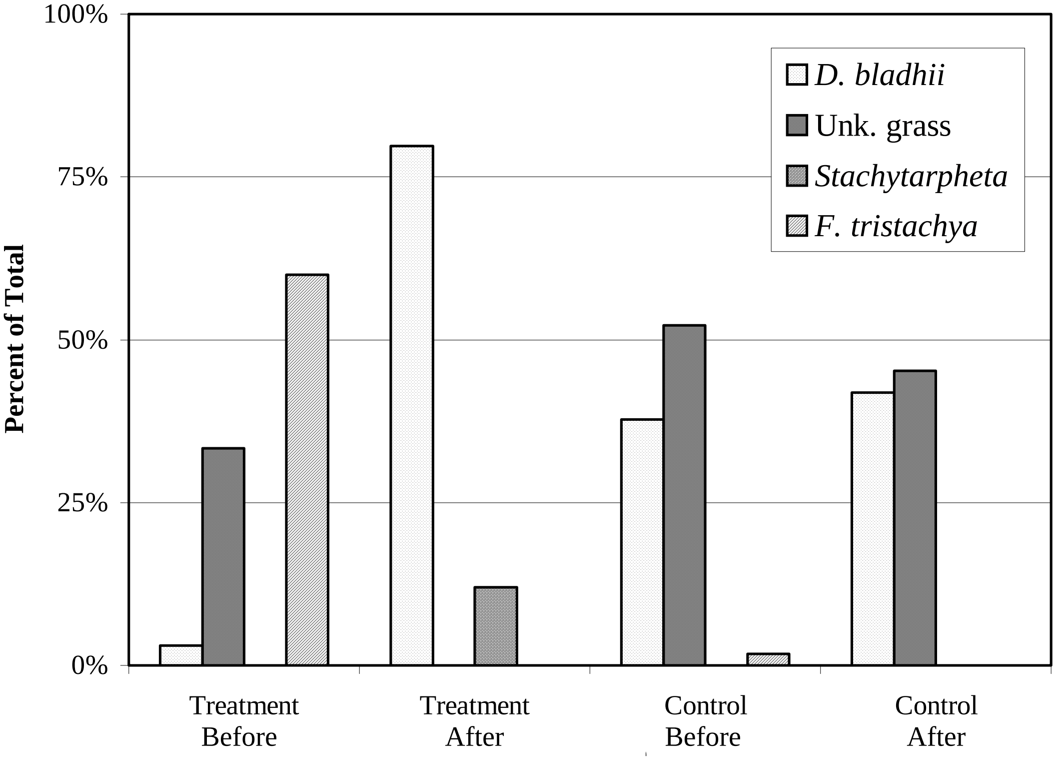

Figure 3-4. Percent of total biomass for common species in flume study in treatment and control plots before and after administering a controlled burn.

promote burning. It is a prolific seed producer (Smith and Knapp 2001) and germinates readily in Guam's acidic savanna soils.

Dicanthium bladhii is a relatively recent arrival to Guam. Stone (1970) did not record the species in 1970, but seventeen years later, Fosberg et al. (1987) lists *D. bladhii* as a significant component of Guam's savanna. This species now appears to be one of the dominant grass species in Asan sub-watershed. *Dicanthium bladhii* comprised a significant percentage of the post burn communities in both the field study (Table 3-5) and controlled burn experiment (Figure 3-4). Six months following a burn, *D. bladhii* comprise as much as 87.7% of the vegetation biomass in our burned plots (Appendix 4). While not as large a component of the total biomass, *D. bladhii* was still the most common species observed in the mixed plots. This value, however, was skewed by a single mixed plot (mixed-4) in which *D. bladhii* comprised over 80% of the plant biomass. In the other three mixed plots, *D. bladhii* did not exceed 25% of the biomass.

Invasive grass species are capable of significantly altering fire regimes (D'Antonio and Vitousek 1992; Mack and D'Antonio 1998) and reducing native species in communities that are not fire adapted (D'Antonio et al. 2000). Both *D. bladhii* and *Pennisetum polystachion*, another invasive grass observed in Asan's savannas, have been linked with altered fire regimes (Fensham and Cowie 1998). Altered fire regimes can generate a positive feed back loop, commonly referred to as the grass-fire cycle (D'Antonio and Vitousek 1992), in which fire tolerant grasses that move into burned areas create conditions that promote further burning and thus further invasion. In experimental investigations, *D. bladhii* increased in dominance with repeated burning, displacing native species in Kansas (Grace et al. 2001) and *P. polystachion* has increased fire frequency and intensity in Australian *Eucalytus* woodlands causing their conversion to *Pennisetum* dominated grasslands (Fensham and Cowie 1998). In the absence of a consistent fire regime, it is unlikely that many of Guam's savanna species developed significant adaptations to survive frequent burning. Our data suggest that Guam's mixed savannas are poorly adapted to, and negatively affected by, high fire frequencies. Few, if any, patches of entirely native mixed savanna probably remain in the Asan sub-watershed. Mixed plots contained on average 55.5% non-native plants, and the presence of *D. bladhii* provides support for continued burning.

The hypothesize vegetation mosaic is probably the result of variable fire return frequencies for specific geographic locations within the savanna. A detailed long-term fire history of the Asan sub-watershed does not exist, but over the two years of this study, four fires burned over 6% of the sub-watershed's savanna. This burn frequency is in agreement with recent US Forest service estimates for Guam that estimated the Piti-Asan watershed received 1-3 fire per year (Neill and Rea 2004). The fires observed in the study were geographically close together, suggesting that this area of the Asan sub-watershed has a high fire return frequency. While not observed during this study, fires have burned in nearly all areas of the watershed where savanna vegetation can be found (Minton pers. obs.).

The presence of *D. bladhii* in a plot may be an indicator of past burning. *Dicanthium bladhii* was present in all of our mixed and burned plots except mixed 2, suggesting that all but this plot have been burned in the recent past. The limited fire history gathered as part of this study suggests this is highly probable.

The mixed savanna subtype appears to be the most fire sensitive. No fires were observed in the fern subtype. Ferns in the Asan sub-watershed do not appear to burn easily and, on several occasion, fires in the mixed savanna were observed to have go out upon reaching the edge of a fern subtype. Swordgrass, *Miscanthus floridulus*, appears to be well adapted to burning (Stone 1970). It is capable of resprouting quickly from its root mass following fire (Wang et al. 2003). *Miscanthus floridulus* has a widespread distribution across the Asia-Pacific region and it is unclear if this species originally evolved in a system with natural fire prior to its arrival on Guam. This species is tolerant of poor soil conditions and initially it may have survived on Guam by growing on steep slopes where soil quality was lower than on flat areas. With the arrival of fire to Guam, the distribution of this species is believed to have increased (Stone 1970). Unfortunately, the swordgrass plots installed for this project could not be relocated and the vegetation was not measured.

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Chapter 4.
Upland Erosion

Introduction

Many of Guam's native vegetation communities require specific soil characteristics for survival. Savanna vegetation grows in soils formed from volcanic parent material (Stone 1970). These weathered soils are acidic (pH <5.0) and nutrient poor, with low permeability (Stone 1970). Changes in soil quality or quantity can adverse affect vegetation communities, causing changes in abundance (O'Dea and Guertin 2003) and shifts in plant species composition (Woube 1998).

On southern Guam, upland erosion is the primary threat to both terrestrial and aquatic ecosystems. Erosion removes the topsoil layer, exposing inhospitable clays to plant root systems. Soil pH, nutrient, organic material and metal concentrations, texture, cation exchange capacity, and permeability can all be altered by soil loss. Eroded soils transported into streams can alter water quality (Neubauer 1981; Townsend and Douglas 2004) and negatively impact coast marine ecosystems, such as coral reefs (Fabricius 2005).

Most of our understanding of erosional processes comes from agricultural research, but has applications in natural systems. The Revised Universal Soil Loss Equation (USLE model) predicts the long-term average annual soil loss from specific field slopes (Renard et al. 1997). In this model, five major factors affect soil loss, of which the first four are directly relevant to natural ecosystems. These factors include:

1. Rainfall and runoff (R). The greater the intensity and duration of a storm, the higher the erosion potential
2. Soil erodibility (K). This is a measure of susceptibility of soil particles to detachment and transport by rainfall and runoff. Texture is the principal factor that affects erodibility, but structure, organic matter and permeability also contribute.
3. Slope length and gradient (LS). The steeper and longer the slope, the higher the risk for erosion.
4. Vegetation cover (C). The type and amount of vegetation will affect soil loss.
5. Conservation practice (P). Different land management strategies (e.g. tilling practices, crop rotation strategies) affect erosion rates. This factory is not as applicable in the natural environment, but is important when considering restoration activities (Chapter 7).

Guam experiences high annual rainfall (>250 cm per year) with 70% occurring during the island's wet season (July-December) (Lander and Guard 2003). During the wet season, the island often experience large, intense rain events in the form of tropical storms and cyclones. During 2002, Guam experienced two typhoons that had hourly rainfall rates in excess of 15 cm (Lander and Guard 2003).

The physical and chemical properties of Guam's soil make it particular sensitive to degradation. The soils in the Asan sub-watershed belong to the Akina series (Akina-badland Complex) (Young 1988). The topsoil layer is thin (A Horizon:1-10 cm) silty clay with low pH (~5.0). The subsoil (B Horizon) which may extend to 50 cm depth, is very strongly acidic (pH 4.9-5.1) clay. The underlying substratum (C Horizon) is predominantly fine acidic clays that contain little to no nutrients and organic matter and have very poor infiltration rates, creating rapid runoff and the potential for severe erosion (Young 1988). Coupled with the steep terrain, these characteristics make the soil highly susceptible to degradation from erosion. In areas where the upper soil horizons have been removed, the exposed underlying saprolites are incapable of supporting vegetation. These areas devoid of vegetation are referred to locally as "badlands" (NRCS 1996) and are described Young (1988) as actively eroding areas.

Guam's savannas are primarily a xeric ecosystem characterized by a relatively continuous grass layer intermixed with solitary trees and bushes and bare patches of exposed saprolite clay (Raulerson 1979). Stone (1970) recognized four subtype communities in the savanna: 1) *Miscanthus*, 2) *Dimeria*, 3) erosion scar, and 4) *Phragmites* (see Chapter 3 for a more detailed description). While little research has examined the soil requirements for each subtype, observational data suggest that each subtype may have different preferred soil conditions. The *Miscanthus* subtype prefers steep slopes with relative poor topsoil. The *Dimeria* subtype is often found on flat areas, where top soil layers a re thicker and probably less acidic. The erosion scar subtype is found along the edges of badland formations where top soil is nearly absent and aluminum concentrations are very high. The *Phragmites* subtype prefers water-logged soils.

Vegetation plays an important in mediating erosion by protecting soil from raindrop impact and by holding soils with roots. The ability to protect soil from erosion will vary by species, as different vegetation growth forms provide different levels of protection. In savanna grasses species, for example, bunch (caespitose) grasses, such as *Miscanthus*, provide lower erosion protect than non-bunch grasses, such as *Dimeria*. Species with high above biomass in the form of leaves (e.g. *Miscanthus*) provide better erosion protection than species with lower above ground biomass (e.g. *Dimeria*).

While several recent studies have estimated erosion rates in Guam's savanna (NRCS 1996, 2001; Scheman et al. 2002), none has examined the effect of vegetation subtype on erosion rates. Guam's savannas are a mosaic of subtype patches that are maintained and continuously modified by frequent burning (Chapter 3). Under the current anthropogenic fire regime, conversion of savanna to different subtypes, and eventually to badlands, may be happening at an accelerated rate. It is critical to understand how vegetation subtype, as well as badlands and burning, affect erosion rates. This chapter discusses efforts to measure seasonal erosion rates in three of the four savanna subtypes (excluding the *Phragmites* subtype), burned savanna, and badlands.

Materials and Methods

Rainfall

Rainfall for the period January 2002 through June 2005 and monthly rainfall averages were obtained from the Tiyjan Guam office of the National Weather Service. Monthly averages were calculated based on monthly rainfall rates from 1945-2002 and were used to compute average rainfall in wet and dry seasons.

Erosion Measurements

At the start of this research, no vegetation habitat maps were available for the Asan Inland Unit of War in the Pacific NHP. To select sites, 200 random points were generated using ArcGIS and overlain on 2002 IKONOS imagery. Any points that occurred in forested vegetation were excluded from further analysis and all remaining points were field investigated to determine savanna habitat type and slope. Vegetation cover was visually estimated as percent coverage of swordgrass (*Miscanthus*), fern (*Dicranopteris*), and grass (other than *Miscanthus*). Random points were systematically investigated until four sites with similar slope (between 9 and 12%, as measured with an inclinometer) were obtained for each of the following habitat types: 1) mixed; 2) swordgrass; 3) fern; 4) burned; and 5) badland.

In June of 2003, four mixed and three burned study plots were established prior to onset of the wet season (Figure 4-1). Burned plots were established following a June 2003 fire in the Asan Inland Unit of war in the Pacific NHP. Randomly selected sites were investigated until plots meeting the selection criteria were located. Because of the relatively small size of the burn, only three suitable sites were found. Following the wet season, four fern and four swordgrass plots were installed. Because of the dense nature of swordgrass, these plots were never successfully relocated and will not be discussed further in this report.

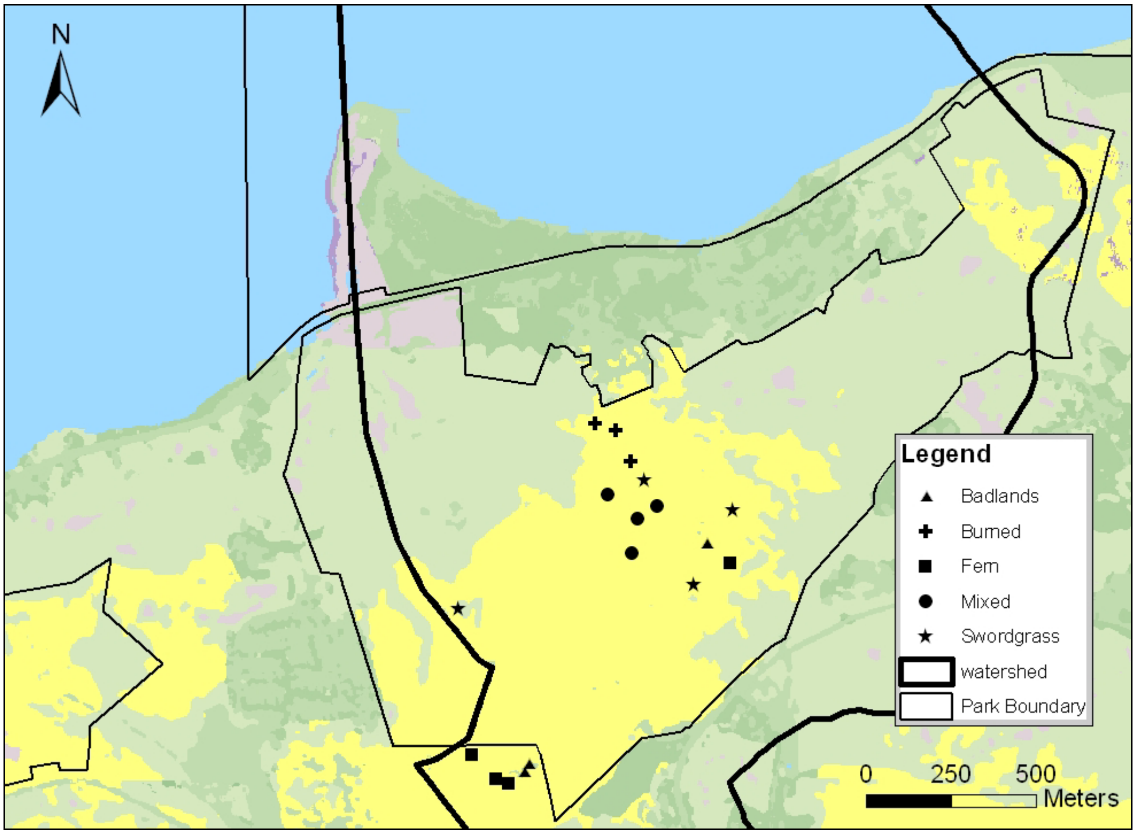

Figure 4-1. Location of erosion study plots in the Asan sub-watershed.

At each study plot, a 10 x 10 m erosion pin plot was installed (Figure 4-2). Pin plots were established parallel to prevailing slope. Five rows of nine erosion pins running perpendicular to the slope were installed. Rows were two meters apart and pins within each row were 1 meter apart. In total 45 pins were installed into each plot. Pins consisted of metal wire (approximately 1 mm in diameter) up to 20 cm long driven into the ground until flush with the surface of the soil. In some plots, shorter wire was used because the top soil layer was too shallow to accommodate a longer pin and the underlying clays were too hard. Pins as short as 2 cm were used in some locations.

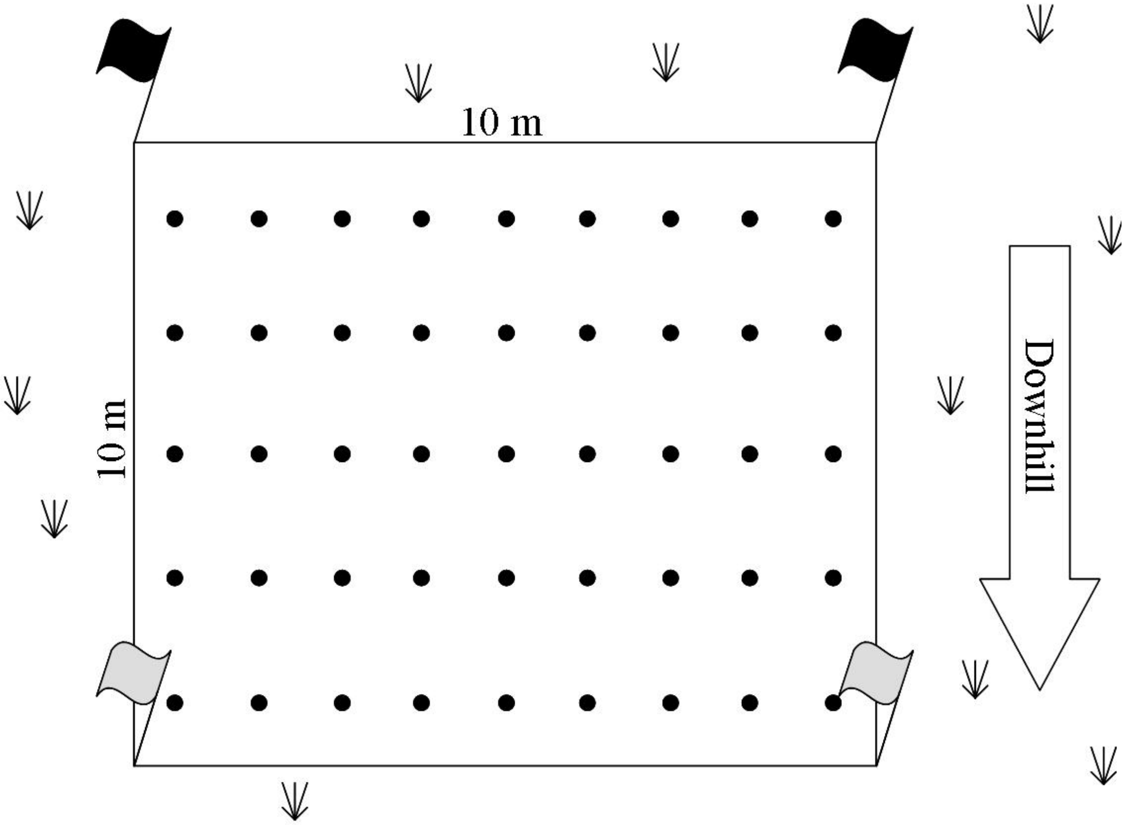

Figure 4-2. Erosion pin plot schematic. Blue flags were installed on the upslope corners, and red on the downslope corners to allow easier relocation. Pins were installed in five rows of nine pin running perpendicular to the direction of the slope.

In January and June of 2004-2005, pins were relocated using a metal detector. The metal detector was used to narrow the search to a few square centimeters. Visual searches were then used to locate exposed pins. In instances when visual surveys could not locate the pin, it was assumed that the pin was buried. Searches were conducted for at least 3-5 minutes before designating the pin as buried. In some plots, discarded metal proved problematic, but searches were conducted until all stray metal pieces were removed from the pin area. Subsequent searches were thus less difficult. Pin detection rate, based on pin relocation data, was high. Pins with 1-10mm exposed had a 73% detection rate. Pins with >10mm exposed had a 93% detection rate. Pins with <1 mm exposed had the lowest detection rate (43%), but this included pins that were assumed to be buried.

Digital calipers were used to measure the amount of the pin exposed to the nearest 0.01 mm. Pins were measured from the top of the pin to the ground surface when erosion was even on all sides of the pin. If erosion was not even on all sides of the pin, erosion was measured as the average of the minimum and maximum erosion (Figure 4-3). Pins that were found but not exposed were recorded as 0.01 mm exposed. Pins that were not visually located were analyzed as zero exposed. Using a zero for unfound pins generates a maximum erosion value, as these pins may be buried, signifying accumulation. The method used does not allow accumulation to be measured.

To estimate tonnage, three 100 cm^2 soil samples were haphazardly collected from the savanna. Soil samples were dried at 100 ºC for 24 hours and weighed to the nearest gram using an electric balance to determine a volume to tonnage conversion factor. The volume of soil lost was calculated as a cube with dimensions equal to 10 m by 10 m by the average erosion as measured by the erosion pins. This volume was converted to tonnage by multiplying by the conversion factor.

For each plot, a mean soil loss was computed by averaging the soil loss measure by the 45 pins. This mean value for each plot was used in an ANOVA with vegetation plot type and season. The model fit was investigated by examining the residuals. *A priori* contrasts were conducted comparing between seasons and among vegetation types. An overall error rate of α=0.05 was maintained using Tukey's method. All errors are expressed as standard errors of the mean (±SE).

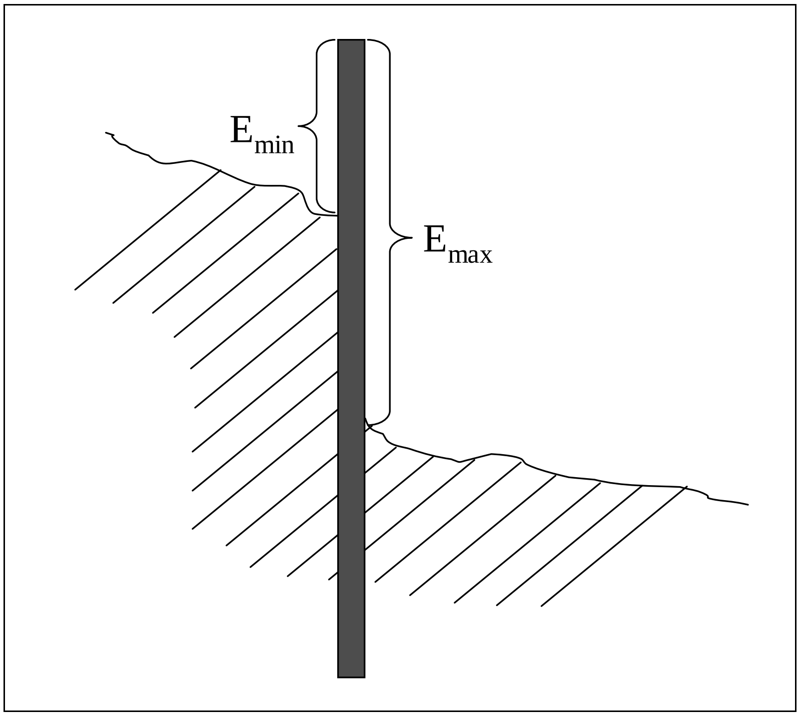

Figure 4-3. When erosion was not even around a pin, soil loss was calculated by taking the mean of the maximum (E_{max}) and minimum (E_{min}) erosion measurements.

Results

Rainfall

Guam rainfall shows a distinct seasonal pattern (Figure 4-4). The dry season (January-June) receives on average 10.3 ± 1.4 cm/month, compared to 25.5 ± 3.2 cm/month in the wet season (July-December).

The year 2004 was an exceptionally wet for Guam. The 154 cm of rainfall at the Guam International Airport made it the second wettest year dating back to 1950 (PEAC 2005). The summer rainy season was very wet with high monthly variability. Peaks in June and August were associated with two typhoons that passed close to the island. Typhoon Tingting (June 27-28) and produced over 50 cm of rain in a 24 hour period. Typhoon Chaba passed near Guam on August 21 and produced heavy rains with a peak 24-hour total of 9.05 inches (PEAC 2005).

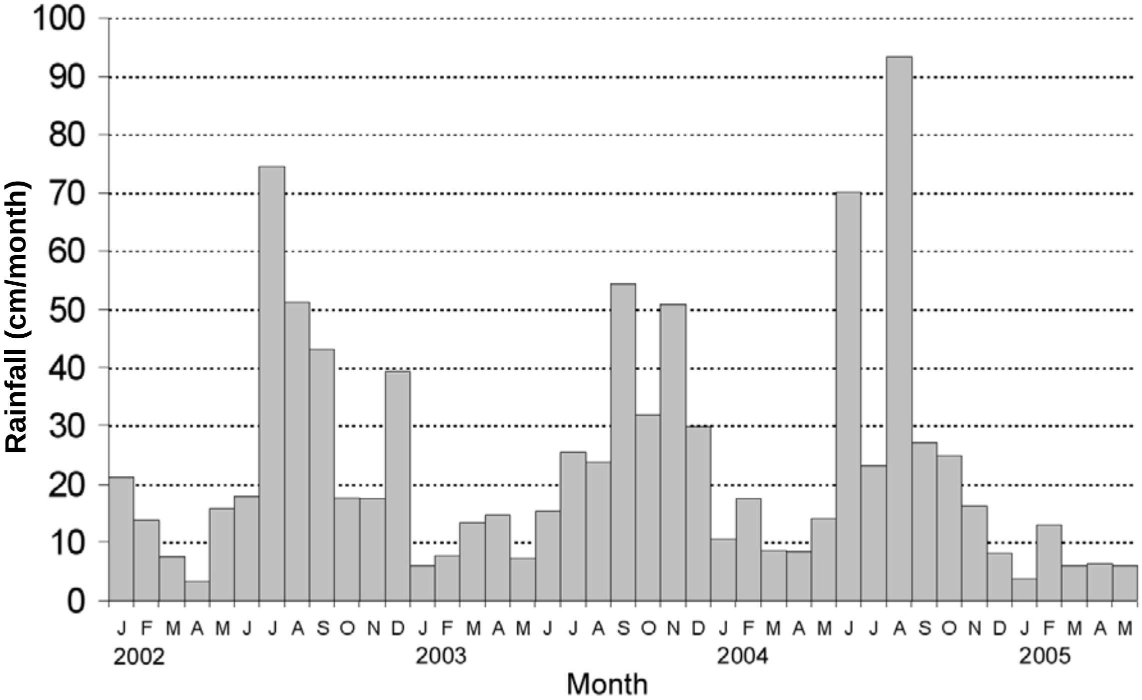

Figure 4-4. Monthly rainfall (cm/month) for January 2002-May 2005. Pattern shows a distinct yearly dry (Jan-June) and wet (July-Dec) season.

Erosion

The slope of the study plots did not significantly vary with plot type (ANOVA, F=1.03; df=3,10, p=0.42). Slope measurements varied from a mean of 5 ± 0.6 degrees in mixed plots to 11.3 ± 4.2 degrees in burned plots.

Soil loss differed significantly with season (ANOVA; F=6.48; df=1,38; p=0.015) and vegetation type (ANOVA; F=5.65; df=3,38; p=0.003). The vegetation type by season interaction was not significant (ANOVA; F=1.06; df=3,38; p<=0.375) Erosion was significantly higher in the rainy (3.6 mm ± 0.3 mm) than dry (1.8 mm ± 0.2 mm)

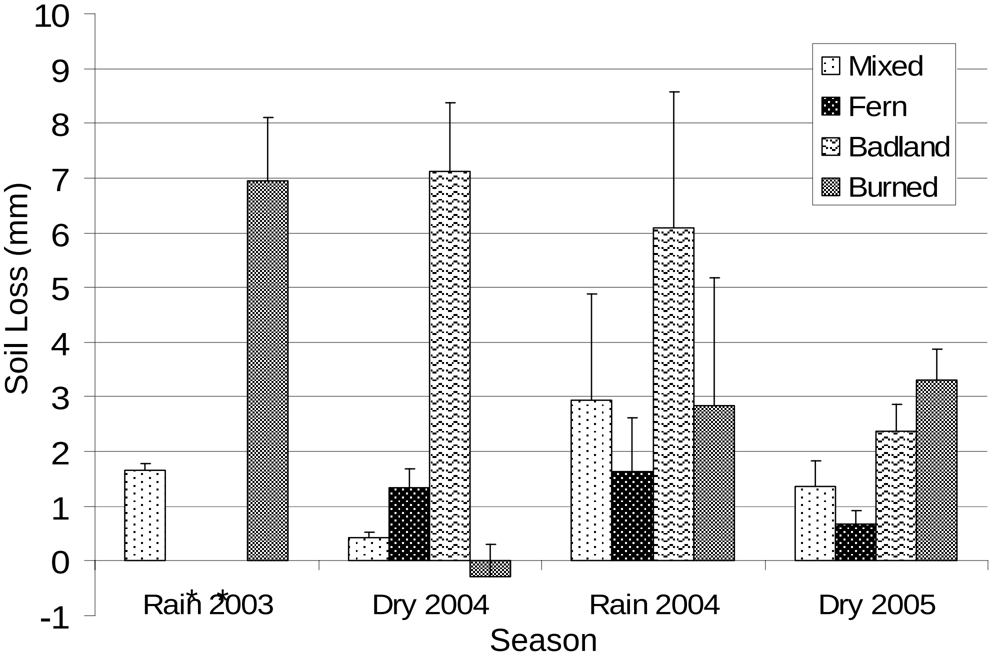

Figure 4-5. Soil loss (mm) by vegetation type and condition. Soil loss is the mean (error bars = +SE) length exposed on erosion pins (45 pins per plot) in four mixed and fern plots and three burned and badland plots. *=No data were collected for the fern and badland plots in 2003.

season across all vegetation types (Figure 4-5). No significant difference in soil loss was observed between the dry 2003 and dry 2004 seasons, but the Rain 2003 season (4.3 mm ± 0.5 mm) experienced significantly higher erosion than the Rain 2004 season (3.2 mm ± 0.3 mm).

Badlands experienced the highest overall erosion rate (5.2 mm ± 0.4 mm), which was significantly higher than the mixed and fern plots, but not significantly different from the burned plot. Burned plots (3.2 mm ± 0.4 mm) did not significantly differ from the mixed (1.6 mm ± 0.2 mm) or fern (1.2 mm ± 0.2 mm) plots. Mixed and fern plots were not significantly different from each other. Soil loss was converted to metric tons per hectare (Table 4-1) using 1 cm^3 of soil weighing 0.72 g.

Table 4-1. Soil loss in millimeters and tones/ha for mixed, fern, badland, and burned plots.

	Rain Season		Dry Season	
Plot Type	**Soil Loss (mm)**	**Tonnes/ha**	**Soil Loss (mm)**	**Tonnes/ha**
Mixed	2.3 (SE)	16.6	0.9	6.4
Fern	1.6	11.7	1.0	7.3
Badland	6.1	43.9	4.7	34.2
Burned	4.9	35.3	1.5	10.8

Discussion

The presence of vegetation cover plays a significant role in decreasing the rate of soil loss, but the type of vegetation present, and specifically the species composition, appears to have a minor effect on erosion rate. Both mixed and fern plots showed no significant difference in soil loss, and their soil loss rates were almost identical (Table 4-1). While burned plots showed higher rates than both the mixed and fern plots, the difference was not statistically significant at $\alpha=0.05$. However, the pattern of soil loss on burned plots, was illustrative. Following a fire, when most of the above ground vegetation biomass had been remove, erosion rates in burned plots were comparable to badlands (Figure 4-5). The following season, after grass had re-grown in the burned plots, erosion rates were comparable to grass plots. While the vegetation in the burned plots was dominated by invasive grasses (Chapter 3), the ability of this community to hold the soil was not significantly different from mixed and fern plots. However, a real trend in elevated erosion rates on burned plots in all seasons is present, as suggested by the absence of a significant vegetation type by season interaction. Whether this higher erosion rate is significant, and the lack of statistical validation is simply the result of low sample size, is unknown. These results are also confounded to some extent by the previous burn history of the area and the highly variable vegetation mosaic that appears to comprise the watershed's savanna, especially the mixed savanna subtype (Chapter 3). This variability in the species composition of the mixed plots would act to obscure burn effects, further suggesting that the observed trend of higher erosion rates on re-vegetated burned plots, while not statistically significant, is real.

In the Fena watershed on southern Guam, savanna that had been 18 months previously was estimated to have 33% higher erosion than unburned savanna (NRCS, 2001). In Asan, savanna burned 18 months previously (June 2003) had erosion rates over twice that of previously unburned mixed savanna, 3.3 ± 0.6 mm compared to 1.4 ± 0.5 mm in the 2005 dry season. These results further suggest that the new vegetation community, one dominated by introduces grasses (Chapter 3), does not hold soil as well as the mixed savanna subtype. The exact reasons for this difference are unclear at this time, but it may be related to changes in grass growth form and/or to the presence/absence of an organic mat. In much of the unburned savanna, a thin, organic mat, its exact composition unknown, covers the ground, keeping the soil moist and presumably reducing erosion. Following burns, this mat is destroyed, and soils tend dry out and scarify (Minton pers. obs.). Eighteen months following burning, this organic matting was still absent at the burned plots.

Unfortunately, efforts to measure erosions rate in swordgrass plots were unsuccessful, but observations suggest that erosion in this savanna subtype is higher than in the mixed and fern subtypes. *Miscanthus floridulus* is a bunch grass and many of theses swordgrass bunches are pedestaled (Minton, pers. obs.), suggesting increased sheet and rill erosion between the clumps.

Erosion rates immediately following a burn were as high as in badland areas, even though burned areas still had many root crows still place (Minton, pers. obs.). The root crowns appeared to have little effect on the rate of soil loss. Additionally, the burned plots re-sprouted within a few weeks of burning and after approximately 6 months, there was no significant difference in plant biomass among the plots, although a trend toward lower biomass in the burned plots was observed (Chapter 3).

The higher erosion rates observed during the 2004 wet season compared to the 2003 wet season (Figure 4-5) are mostly likely the result of higher rainfall. Interestingly, the wet season in 2003 had more large rain events (>2.5 cm) than did the same period in 2004, 27 compared to 23 events, but the 2004 wet season had two very large storm events. Typhoon Tingting (June 28-29, 2004) dropped over 50 cm of rain and typhoon Chaba (August 21) produced heavy rains with a peak 24-hour total of 9.05 inches (PEAC 2005). The most significant rain event of 2003 occurred during November, when Typhoon Lupit passed south of the island and deposited over 15cm of rain (PEAC 2004).

High soil erosion rates have been reported for many countries in the tropics (Lal 1995a). The rates measured at in this study exceed the reported rates in many countries (summarized in Lal 1995a), including Brazil (18-20 tonnes/ha/yr), Guatemla (5-35 tonnes/ha/yr), Guinea (18-25 tonnes/ha/yr), , and Peru(15 tonnes/ha/yr), and are comparable to rates observed in Jamaica (90 tonnes/ha/yr), Madagascar (25-250 tonnes/ha/yr), Nigeria (15-300 tonnes/ha/yr), and Papua New Guinea (6-300 tonnes/ha/yr). These high erosion rates have been reported in connection with tropical farming, which can dramatically increase erosions rates (Lal 1995b).

Since 2001, two projects have investigated erosion in two southern Guam watershed, the Fena watershed (NRCS 2001) and the La Sa Fua watershed (Scheman et al. 2002). Erosion rates estimated in the Fena watershed (NRCS 2001) were considerably higher than those recorded in this study. These values (Table 4-2) were estimated using the RUSLE equations for the entire watershed and include much steeper slopes than measure in current project. The Fena estimates also do not divide the savanna into vegetation subtypes. At La Sa Fua (Scheman et al. 2002), erosion rates measured empirically were more comparable to those measured in this study (Table 4-2). Erosion rates calculated for the same watershed using RUSLE were considerably higher, raising concerns about the accuracy of the RUSLE results on Guam. Reasons for the large discrepancy between the RUSLE and the empirical estimates at La Sua Fua are unclear.

Table 4-2. Sheet and rill erosion rates (tonnes/ha/year) estimated in the Asan, Fena, and La Sa Fua watersheds on Southern Guam. Estimates from Fena were obtained from NRCS (2001) and estimates from La Sa Fua were modified from Scheman et al. (2002).

			La Sa Fua	
Vegetation	**Asan**	**Fena**	**Empirical[1]**	**RUSLE**
Savanna, unburned	21[2]	110[3]	2	4[3]
Savanna, burned	46	146[4]	-	-
Riverine Forest	-	70	-	-
Limestone Forest	-	1.8	-	-
Badland	78	539	92	543

[1] Value calculated as the mean of the steep and valley plots

[2] Calculated as the mean of mixed and fern subtypes for the entire year

[3] Contains all vegetation subtypes

[4] Savanna was burned 18 months previously; estimated to be 33% higher than unburned savanna.

While not measured as part of this study, erosion has well-documented, adverse affects on soil quality (Lal 1995a; Giovanni and Luccesi 1997; Kaihura et al 1999; Ternan and Neller 1999). Changes in soil quality may affect the overlying vegetation and thus alter subsequent erosion rates. If the new vegetation community does not hold soil as well as the original native vegetation, this may create a positive feedback loop that ultimately destroys soil quality to the point that vegetation can no longer survive. The badlands present on Guam may be a direct result of this type of process.

Soil at the Asan study sites belongs to the volcanic Akina-Badland complex (Young 1988), which is characterize by very low pH and high erodibility. The topsoil is thin, on the order of 10 cm deep (Figure 4-6). At the erosion rate observed following a fire (~7 mm), 10 cm of topsoil could be lost with fifteen burns, exposing the underlying sapprolite which is strongly acidic (pH<5.0) and has high concentrations of aluminum. In some areas of the Asan watershed, fire return rates are high, probably on the order of 1-3 years. However, the Asan grasslands have existed for many years, and at least as far back as the 1940s, suggesting the other factors are at work to maintain hospitable soil conditions. The timing of fire in the savanna certainly plays a key role in erosion. The majority of fire on Guam occurs from March to May, at least two months before the onset of the wet season. Even in the dry season, Guam's savanna receive sufficient rainfall to allow plant re-growth. Fire that occur later in the dry (e.g. June) are likely to have greater adverse effects on the watershed's soil quality.

Figure 4-6. A soil cross-section in Asan sub-watershed. A thin topsoil layer (dark brown) overlies sapprolitic clays (light brown). The white bar is approximately 10 cm long.

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Chapter 5.
Erosion Flumes

D. Minton, M. Golabi, and C. Iyekar

Introduction

Soil erosion is a significant environmental threat throughout the tropics, and high erosion rates have been documented in many tropical countries including Jamaica, Brazil, Guatemala, Papua New Guinea, Thailand, China, Nigeria and Madagascar (Lal 1995a). Erosion degrades soil quality by removing topsoil, altering soil pH, lowering nutrients and organic material, altering texture and permeability, and lowering the cation exchange capacity (CEC) (Lal 1995a, 1995b; Giovannini and Lucchesi 1997; Kaihura et al. 1999; Ternan and Neller 1999; Wang et al. 2003). Soils transported into streams can adversely affect water quality (Neubauer 1981; Townsend and Douglas 2004) and habitat quality. Sediments flushed into the nearshore marine environment can adverse impact coral reefs through a variety of direct and indirect pathways (Fabricius 2005).

On Guam, erosion is a significant issue to both the terrestrial and aquatic environments (Birkeland et al. 2000). Erosion rates measured in the Ugam (NRCS 1996), Fena (NRCS 2001), La Sa Fua (Schemen et al. 2002) and Asan (chapter 4) watersheds are higher than many published reports from the tropics (Lal 1995b). Much of the erosion is attributed to badlands, or areas of accelerated erosion incapable of supporting vegetation (Young 1988). While these areas may cover only 1% of the entire area of Guam, badland areas contribute a disproportionate amount to soil loss (Schemen et al 2002).

Badlands are composed of strongly acidic (pH=~5.0), highly erodible, saprolite clays with poor permeability and high concentrations of aluminum (NRCS 1996). Because of low infiltration rates, storm water runs off badlands as sheet flow, promoting sheet and rill erosion and gullying, which can account for 93% of the erosion in southern Guam (NRCS 2001). These factors also contribute to the inability of plants to easily re-vegetate these regions.

Reducing erosion in badland areas is critical to reducing terrestrial soil loss and coastal sedimentation. Current restoration efforts in badlands have focused on the introduction of invasive *Acacia auriculiformis* (Dave Limtiaco pers. comm.). This species is fire tolerant, can grow in acidic soils, and can effectively reduce soil erosion rates (Pinyopusarerk 1996). Unfortunately, this species is invasive in the Pacific Islands (PIER 2003). Other efforts to control badland erosion include the installation of coconut fiber matting and organic mulching (NRCS 2001; Robert Wescom, pers. comm.), but these techniques are not long-term solutions. The ideal long-term solution is to revegetate badland areas with native species. This chapter examines the efficacy of using vetiver and sunnhemp technology to reduce soil erosion, improve soil quality, and facilitate badland rehabilitation.

Materials and Methods

This projected was conducted at a forest restoration site under the control of Guam Department of Agriculture, Division of Forestry adjacent to Cross Island Road (Route 17), approximately 4.5 km east of the village of Santa Rita.

Four plots measuring 21.9 m by 1.7 m (72' by 5.5') were established on a uniformly sloped (12%=21.5 degrees) watershed area. In June 2003, four erosion flumes were installed. A backhoe was used to excavate pits measuring 1.5 m x 1.5 m x 1.5 m. A concrete foundation was poured on the bottom of the pits. A concrete retaining wall was installed on the side of the pit adjacent to the end of the flume to hold the soil from caving in. A 250 gallon plastic water tank was placed into the hole and back-filled with dirt. To provide ballast for the slightly conically-shaped tanks and prevent them from "floating" out of the clay lined holes, 15.25 cm of concrete was poured into the bottom of each tank. A wooden brace was used to provide support for the inside of each tank and to stop the sides from collapsing under the weight of the soil.

Around the perimeter if each plot, a trench 0.02 m deep was excavated with using a trencher with a 10 cm wide blade. Concrete boards (1.9 cm x 16"40.6 cm x 274 cm) were then installed leaving approximately 20 cm above the ground, to make the H-flumes. A weir attached to an end plate that extended 20 cm into each plot was installed at the end of each H-Flume. The weirs at the end of the flumes were attached to an end trough that extended 20 cm into the storage tank (Figure 5-1). A set of suspended sediment samplers were installed in the sampling tanks for measurement of the sediments discharged from the flumes (Figure 5-2).

The samplers were made from two 10 cm diameter by 1.5 m long ABS pipes that were cut long-ways to create four gutter type samplers. The samplers were attached to

Figure 5-1. Runoff storage tanks at the downslope end of the erosion flumes.

Figure 5-2. Sediment sampling apparatus in one of the runoff storage tank.

the end of each weir and were seated on the bottom of the tank at about a 45 degree angle. Five 400 ml cups were seated on a metal wire and were spaced about 10 cm from each other in each sampler. As runoff came down from the weir, it flowed into the first cup. Once the first cup was filled, the run-off is then funneled through the ABS pipe to the second cup, then the third, fourth, and finally the fifth cup. The sediment settled to the bottom of each cup and could be used to estimate total sediment weight. Due to unexpectedly poor weather in June 2003, installation of the flumes was not completed until November 2003.

Four treatments were randomly applied to the four flumes: 1) "as is" or control; 2) no-cover; 3) restoration; and 4) burned. These treatments were selected to represent a wide range of conditions that occur in a typical southern Guam watershed. The control flume received no vegetation manipulation and the existing savanna species were left "as is." The vegetation in this flume was of a mixed savanna subtype (see Chapter 3). In the no-cover flume, all vegetation was tilled and the soil was left exposed. This represented a worst-case scenario, akin to badlands or poorly managed agricultural or construction sites. In the restoration flume, the initial vegetation was remove via tilling and a combination of vetiver and sunnhemp technology were applied to the flume to investigate the potential of these plants to reduce erosion and enhance soil quality. Vetiver grass (*Vetiveria zizanioides*) has been used extensively throughout Asia, Australia, and the Pacific Islands to control erosion (National Research Council, 1993) and aid in restoration (Troung 2001). Sunnhemp (*Crotolaria juncea*) is nitrogen fixing plant that has been used in the tropics as a green manure to rehabilitate nutrient depleted croplands (Rich et al. 2003). Vetiver was planted in hedgerows 13 feet apart with sunnhemp interspersed between each row (Figure 5-3). The burned flume simulated land denuded of vegetation by savanna wildfires on southern Guam. Control burns were applied periodically (16 Jan 2004, 13 July 2004, and 29 March 2005) to maintain an appropriate burn condition.

For each sampling event, the height of the water was measured in each tank using a meter stick. The volume of water in the tank was calculated assuming the tank was a cylinder with a diameter of 1.22 meters. The run-off sampler was removed from the tank and the 5 sample cups were emptied into a 2.5 liter bottle. The runoff in the tank was agitated with a stick to suspend the sediments. The 2.5 L bottle was filled to top from the agitated tank water, tightly capped, and transported to the lab for further processing. A 100 ml sample was collected from the tank for turbidity determination. The tank was then emptied by using a gasoline powered water pump, cleaned with dust pan and duster to remove excess water and all sediment from the bottom. Sampling began in February of 2004, following the first control burn. Sediment samples were collected twice a week during the wet season (July – December) and once a week during the dry season (December – June).

Samples were brought to the lab and allowed to sit for 48 hours. When the sediments had settled, most of the water was siphoned off using a hand pump and the sample was transferred into a pre-weighed 500 mL beaker and dried at 65°C for 48-72 hours, and weighed. In addition to the sediment sample, sub-samples from the runoff water were also taken for turbidity analysis and sediment quantification. Turbidity was measured using a Hatch 2100 instrument.

Figure 5-3. In the restoration flume treatment, hedges of vetiver grass (*Vetiveria zizanioides*) were planted 4 m apart with sunnhemp (*Crotolaria juncea*) seeded between the rows.

Soil samples were collected from each flume for texture analysis as well as other parameters of soil quality indexes (i.e., organic matter content). The percent organic matter was determined using the modified Black-Walkley Digest method (Sheldrick 1984). Parts per million of potassium, calcium, magnesium, and phosphorous were determined by extracting with ammonium acetate and analyzing with an Atomic Absorption Spectrometer 220 FS.

Results

Average monthly rainfall was significantly higher in the wet (37.7cm ± 9.9) than the dry (8.0cm ± 2.3) season (T-test; T=2.9, df=6, p=0.027). June and August 2004 had over twice the rainfall of other months in the wet season. This could be attributed to two significant storms; typhoon Tingting deposited over 50 cm of rain between June 27-28 and typhoon Chaba passed near Guam on August 21 and produced heavy rains with a peak 24-hour total of 23 cm (PEAC 2005).

During the dry season, almost all treatments behaved similarly and the amount of sedimentation was low (Figure 5-4). In general, little sediment was produced from any of the treatment plots from February 2004 to May 2004. In June 2004, rainfall increased to 74 centimeters (Figure 5-4), the second highest recorded rainfall during the study. In this month, the restoration flume had the lowest erosion rate producing 0.23 t/ha of sediment per month as compared to the no-cover flume that produced 7.3t/ha per month. Although the average rainfall was about the same during the months of June and August, the sedimentation from the no-cover treatment plot was considerably higher in August due to the higher intensity of a major storm event that occurred in this month. Again the restoration flume had the lowest soil loss (Figure5-4).

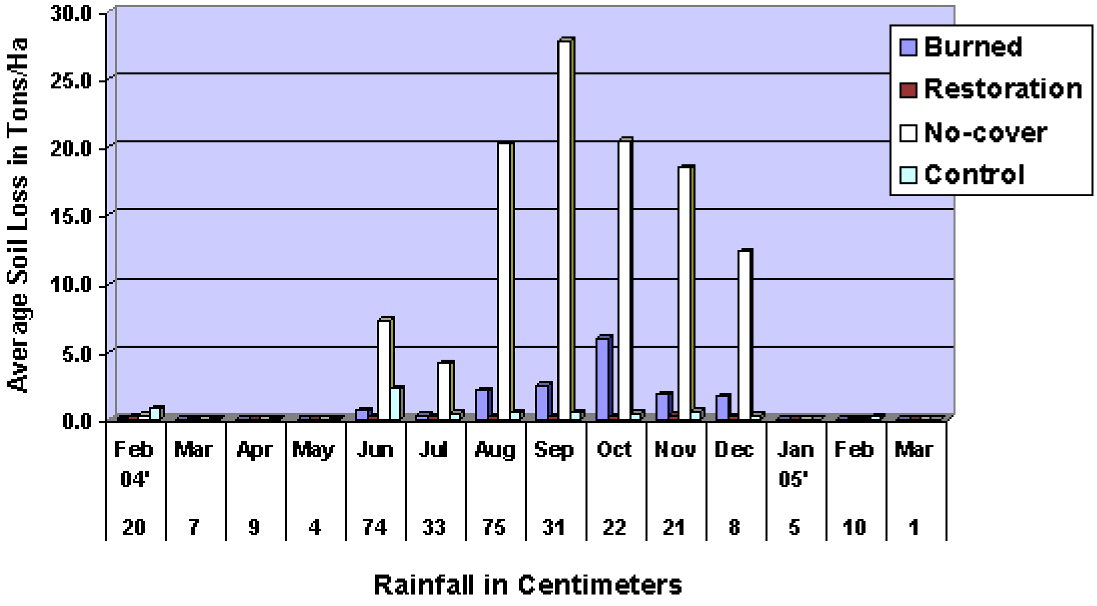

Figure 5-4. Monthly soil loss in the four flume treatments.

Overall, the amount of soil loss was significantly higher in the wet than the dry season (ANOVA; F=33.4, df=1,48, p<0.001) and differed significantly among the four treatments (ANOVA; F=21.3, df=3,48, p<0.001). However, a significant interaction term was present in the analysis, and when investigated, the amount of sediment did not significantly differ between seasons for the control, restoration, nor burned flumes. The no-cover plot had significantly more sediment in the wet than the dry season (Table 5-1). However, if the overall α was raised from 0.05 to 0.1, a significant difference between wet and dry season was also found for the burned plot.

Table 5-1. Amount of sediment (t/ha) in wet (June-Dec) and dry (Jan-May) season for each treatment. Significance tests were performed using a priori multiple comparisons with Tukey's correction for an overall α=0.05

Flume treatment	Season	Erosion (tons/ha)	P
Control	Dry	0.17 ± 0.11	n.s.
	Wet	0.73 ± 0.26	
No-cover	Dry	0.05 ± 0.04	p<0.005
	Wet	15.83 ± 3.10	
Restoration	Dry	0.05 ± 0.03	n.s.
	Wet	0.21 ± 0.01	
Burned	Dry	0.02 ± 0.01	n.s.
	Wet	2.13 ± 0.71	

Soil loss from the restoration and control flumes was highly correlated with rainfall (Pearson's Correlation; p<0.001 for each). Further examination showed the relationships, while significant, were not linear. All plots showed a logarithmic relationship between erosion and rainfall, reaching an asymptotic value unique to each flume treatment (Figure 5-5). All flume treatments appeared to reach the threshold erosion rate at approximately 20 cm of rainfall/month. The no-cover flume had the highest erosion threshold, around 15 tons/ha, and the restoration flume had the lowest, around 0.2 tons/ha. The data had considerable variability, which was probably related to rainfall intensity. The absolute variability was greatest in the burned and no-cover treatments.

Runoff volume was significantly correlated with rainfall (Pearson Correlation; p<0.006 for all treatments), but no treatment produced a significantly different volume of runoff (ANOVA; F=0.17, df=3,52, p=0.915). In June 2004, the restoration flume had abnormally low runoff (Figure5-6), but this may have been the result of measurement error considering the consistency of the monthly trends throughout the course of the project.

The highest turbidity measurements were recorded in August 2004 (Figure 5-7) and corresponded with the highest monthly rainfall. Turbidity was significantly higher in the wet than the dry season (ANOVA; F=7.44, df=1,48, p=0.009). A significant flume treatment effect was also observed (ANOVA; F=9.19, df=3,48, p<0.001), with *a priori* multiple comparisons showing the no-cover treatment to have significantly higher

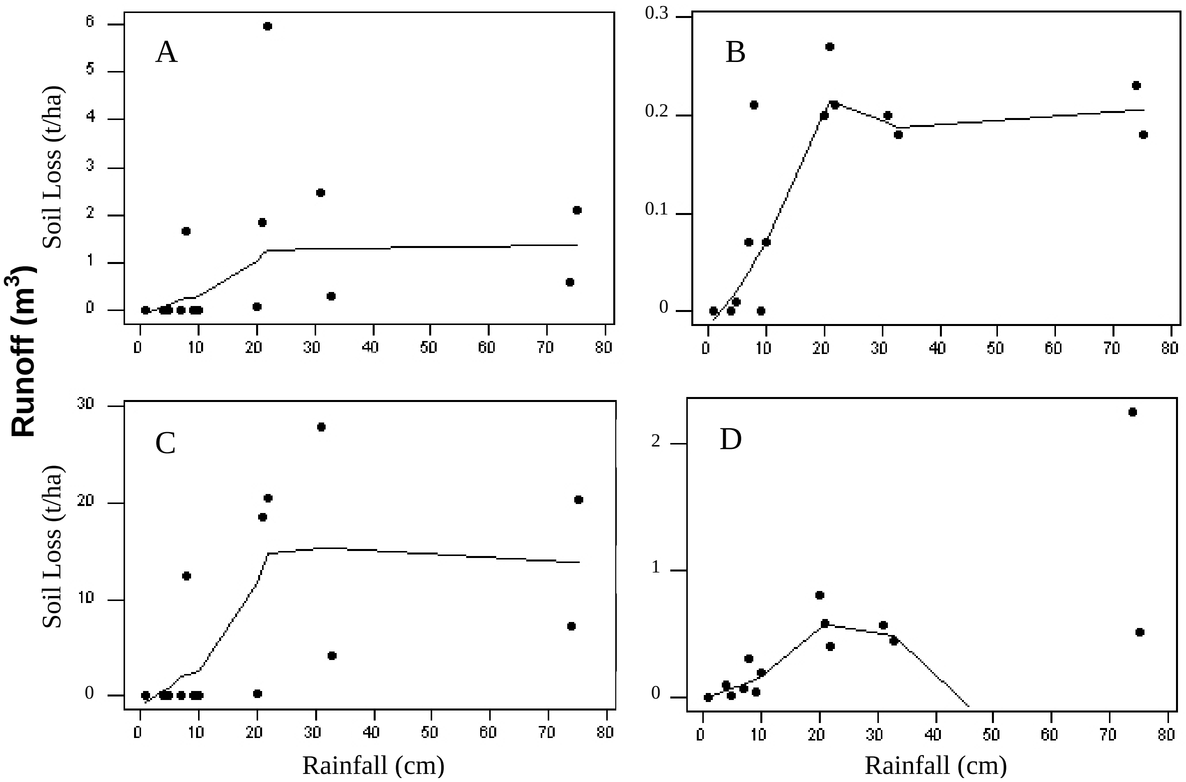

Figure 5-5. Soil loss in each of four flume treatment as a function of monthly rainfall. lowess traces to illustrate non-linear trend in the data. Please note that the y-axis is different for each graph.

turbidity than the other three flume treatments (Table 5-2). The turbidity analysis did not have a significant season by treatment interaction.

Unfortunately, soil quality data from the beginning of the experiment were lost and only summary data is available. Soil texture analysis prior to the start of the experiment revealed that the soil under study site contained 54.4% clay, 20.7% silt and 24.9 % sand, making it a clay soil. The organic matter content of the soils under study was determined to be 3.9% on average. In June 2005, soil quality was re-assessed (Table 5-3), but unfortunately, no comparisons can be made.

Table 5-2. Wet (June-Dec) and Dry (Jan-May) season turbidity (NTUs) measured in the four flume treatments.

Flume treatment	Season	Turbidity (NTUs)
Control	Dry	34.0 ± 10.8
	Wet	41.7 ± 3.2
No-cover	Dry	80.1 ± 24.5
	Wet	142.1 ± 32.2
Restoration	Dry	26.6 ± 6.2
	Wet	40.3 ± 5.4
Burned	Dry	37.6 ± 11.0
	Wet	82.4 ± 16.1

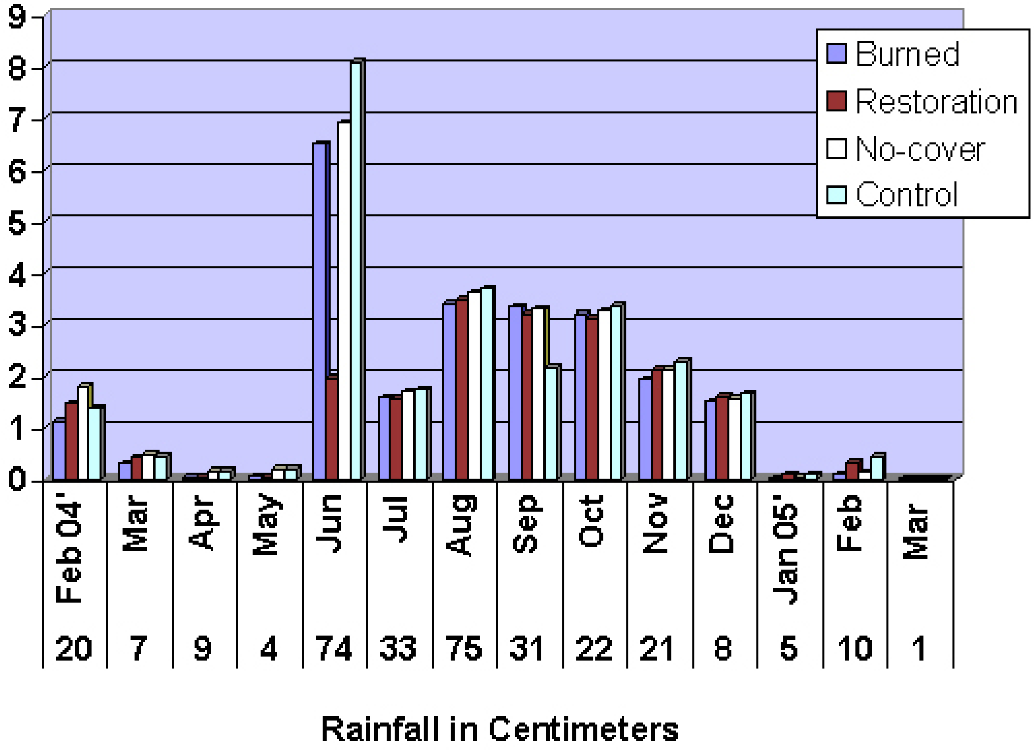

Figure 5-6. Monthly runoff (m^3) collected from each of the four flume treatments.

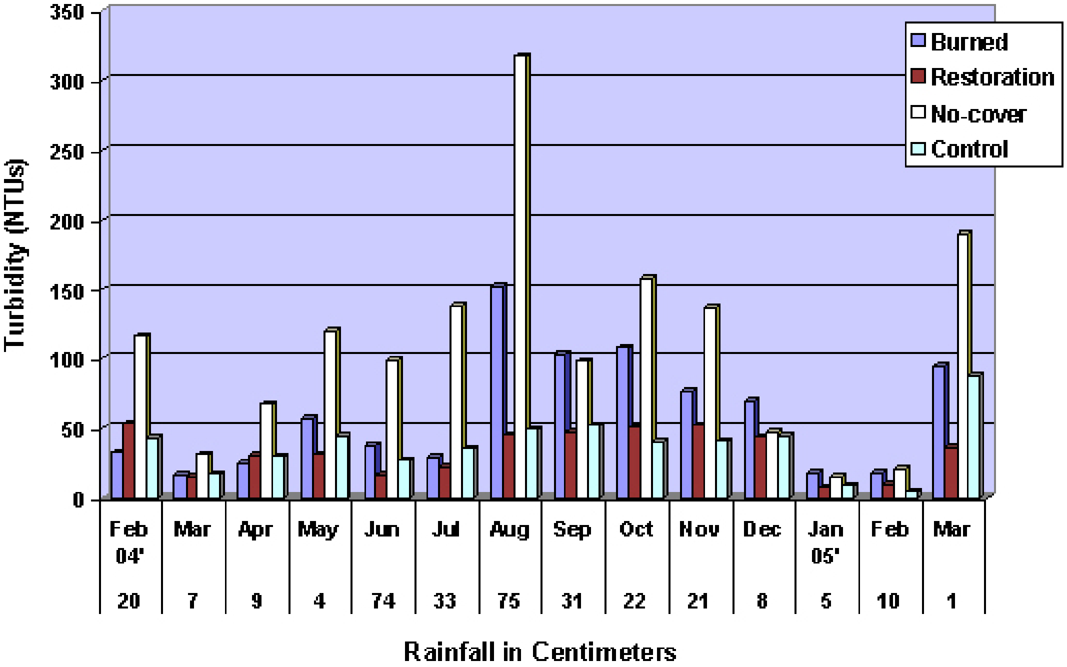

Figure 5-7. Monthly turbidity (NTUs) of runoff measured in the four flume treatments.

Table 5-3. Final soil quality data, measure in June 2005, for each flume treatment.

Flume Treatment	Organic Matter (%)	K (ppm)	Ca (ppm)	Mg (ppm)	P (ppm)	pH
Control	3.8	397	7198	3985	0.50	7.06
No-Cover	5.4	373	5362	5573	0.50	6.22
Restoration	3.0	436	3584	4986	0.63	5.78
Burned	5.1	622	6519	4617	0.63	5.95

Discussion

Erosion and associated sedimentation are the most significant threats to Guam's terrestrial and marine resources (Gawel 1999; Birkeland 2000). On Guam, large areas of exposed soil, known locally as badlands, exist as a result of anthropogenic fire coupled with the island's environmental conditions (i.e. monsoon weather, tropical soils, etc). Guam's badlands have erosion rates six times higher than vegetated savanna (Chapter 4). Because of poor soil quality, badland areas do no readily regenerate, and under the current anthropogenic fire regime (Chapter 3), badland areas are increasing in size and number on Guam. If action is not taken to address erosion issues associated with badlands, these persistent features will continue to have adverse impacts on the islands environment.

Vetiver grass (*Vetiveria zizanioides*) posses several unique characteristics that make it an effective anti-erosional plant, including high biomass, fast growth, and strong, deep root system (Xia and Shu 2003). This study showed that vetiver technology effectively reduced the amount of soil loss and improved runoff water quality compared to plots with no vegetation (Figure 5-8). The restoration flume consistently out performed all other treatment flumes in every measure category.

Vetiver technology shows great promise as a restoration tool for Guam's badlands. Throughout Asia and Australia, vetiver technology has played an important

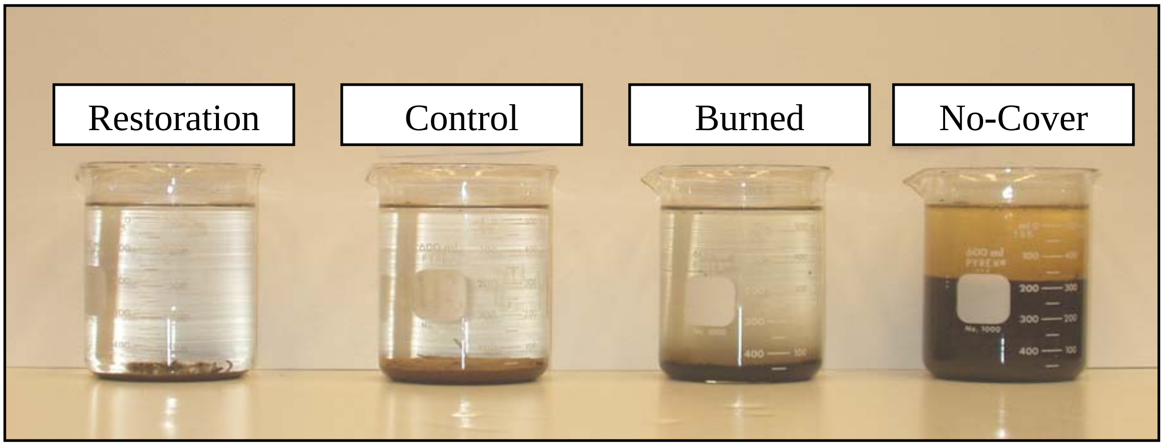

Figure 5-8. Beakers illustrating the water quality (sediments and turbidity) following a major storm event in each of the four flume treatments.

role in reclaiming degraded land for sustainable development or restoration (Troung 2001; Xia and Shu 2003) and may be an effective tool for the short term mediation of badland erosion and for the long term success of restoration efforts.

When used in conjunction with sunnhemp (*Crotolaria juncea*), the vetiver technology may be effective in maintaining or improving soil quality. Badland soils are extremely poor, lacking organic matter, nutrients, and possessing high aluminum concentrations and poor permeability. Sunnhemp is capable of fixing nitrogen and grows quickly, reaching a height of over three meters within 90 days (Anonymous 1996). This above ground biomass can be tilled into the soil to improve the accumulation of organic matter and chemically buffer soils (Rich et al. 2003). Unfortunately, initial soil quality data were lost and assessment of the effects of the vetiver and sunnhemp technology on soil quality cannot be made. Based on the literature, however, it is probably safe to assume that the sunnhemp performed adequately, and at worst, maintained soil quality at the pre-burn levels.

While vegetation plays an important role in reducing soil loss, the timing of burns also may be critical (Townsend and Douglass 2000; Townsend et al. 2004). Controlled burns were applied to the experimental flumes in January and July 2004 and March 2005. Turbidity levels dramatically increased in the months following burning, sometimes disproportionately to the amount of rainfall (Figure 5-6). In June 2004, turbidity in the burned plot was low considering June received 74 cm of rainfall. In August, the month following the control burn, the turbidity had more than tripled with nearly the same amount of monthly rainfall. Over the course of the wet season, turbidity in the burned plot steadily decreased until the plot was re-burned in March 2004. Vegetation re-growth in the burned plot most likely accounts for the observed decrease in runoff turbidity. Elevated turbidity is the result of fine particulate matter, especially clays, in the runoff. While these clays did not contribute significantly to the weight of the soil lost, they present a greater risk to the aquatic environment. Tissue damage to corals increases with increasing sediment organic content and decreasing size (Hodgson 1990; Weber et al. 2004).

While turbidity dramatically increased following a burn, sediment loss did not consistently show the same pattern (Figure 5-4). Following the burns applied in the dry season (July 2004 and March 2005), no increase in soil loss was observed. However, following the burn in the wet season (July 2004), sediment loss increased, especially when compared to June 2004, a month that received high rainfall yet had low soil loss. Dry season rain events appear to be of insufficient intensity to mobilize larger particles, yet are capable of transporting the clay fines that impact water turbidity.

These patterns illustrate the importance of burn timing on soil loss and runoff water quality on Guam. Burns occurring closer to the onset of Guam's wet season are expected to have a larger impact on erosion and runoff water quality than burns conducted earlier in the spring. In addition to the impacts of fine sediments and lower light levels associated with more turbid runoff, aquatic and marine organisms will also be stressed by coarse sediments that can cause burial (Riegl and Branch 1995; Golbuu et al 2003) and disrupt coral energetics (Telesnicki and Goldberg 1995).

On Guam, most burning occurs between March and May (Chapter 3), allowing up to four months for vegetation to re-sprout. To reduce erosion impacts on the island's environment, action should be taken to reduce the incidence of late season burning.

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Chapter 6.
Synthesis

Introduction

While often compartmentalized and studied separately, erosion and sedimentation are part of the same watershed process and must be understood in its entirety to be effectively managed. The only way to successfully mediate nearshore sedimentation is to arrive at a long-term solution to upland erosion. This requires a detailed understanding of the processes involved and the magnitude of the impact associated with each process. If the ultimate cause of the problem is not successfully addressed, any management problem will only serve as a stopgap measure.

This study has attempted to examine the erosion-sedimentation dynamics, including the role of anthropogenic fire, in the Asan sub-watershed to gain a better understanding of the process and to guide resource management and conservation. Chapter 2 examined sedimentation rates on Asan's nearshore coral reefs and raised concerns about sediment levels. Fire effects on vegetation were examined in Chapter 3, and Chapters 4 and 5 demonstrated upland erosion rates among the highest reported in the literature. While the results from each chapter illuminate aspects of this watershed process and suggest viable management solutions, a broader based understanding is needed. This chapter will synthesize information across the watershed in an effort to meet this objective.

On Guam, erosion occurs primarily from the action of water (as opposed to wind) on the island's weathered and highly erodible, tropical soils (NRCS 2001). Steep terrain and monsoonal weather conditions, including frequent large storm events (i.e., tropical storms and cyclones), contribute to the potential for high natural erosion rates. Coupled with human impacts, such as wildland arson and poorly managed development activities, Guam experiences some of the highest measured erosion and sedimentation rates in the world (Chapters 2-5).

In the Asan sub-watershed (Figure 6-1), storm events deposit rain in a seasonal pattern (Chapter 4), with distinct dry (January-June) and wet (July-December) seasons. Rainfall varies from year to year as a function of ENSO events, which have been linked to drought conditions (Lander and Guard 2003). As a result of poor soil infiltration (Young 1988), water deposited in the Asan sub-watershed moves primarily as laminar sheet flow. Some water flows directly into the marine environment as non-point source runoff. The remaining water ends up in flowing into gullies and eventually streams where it is transported through the watershed to the ocean. In the Asan sub-watershed, one primary stream outlet exists (Asan River), forming the sole natural runoff point source.

Along with soil properties and environmental conditions, vegetation cover also plays an important role in upland erosion (Chapters 4 and 5). Any activity that alters the characteristics of the vegetation community can alter the rate of erosion, and on Guam, anthropogenic fire is a significant problem (Niell and Rea 2004). Fire has played a key role in reducing forest cover (Athens and Ward 2004), and appears to be altering the species composition of Guam's native, and currently expansive, savanna ecosystem (Chapter 3).

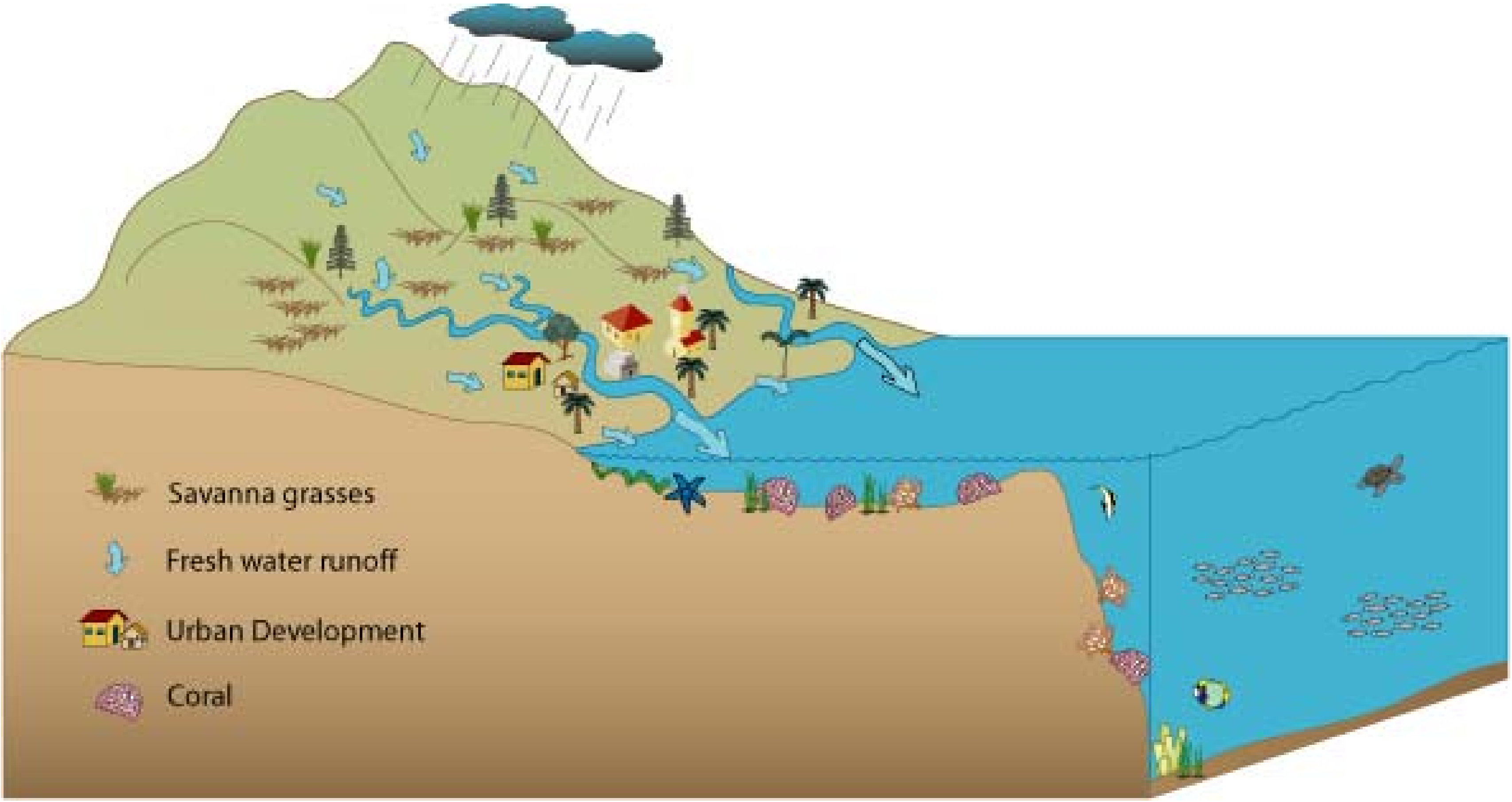

Figure 6-1. Schematic diagram of water flow through the Asan sub-watershed. See text for an explanation.

Given the complex interaction of fire, vegetation, and erosion (Figure 6-2), effective management is problematic unless the numerous interactions can be investigated and understood. In the current climate of decreasing management dollars, it is critical that managers target their limited funding toward activities that will have the greatest environmental return. Each potential interaction needs to be assessed to determine the magnitude and nature of the interaction in order to better understand the process. Ultimately, only a broad understanding of the watershed-level process will make meaningful and appropriate management decisions possible. This chapter will examine sedimentation and soil loss at the watershed scale and will develop statistical models to examine features of the dynamics.

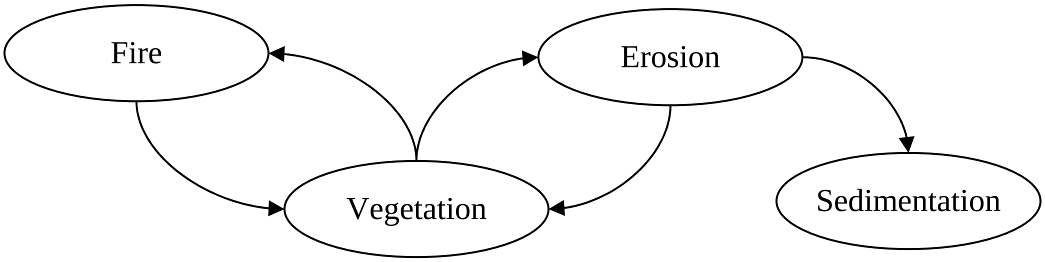

Figure 6-2. Schematic diagram of potential connections among fire, vegetation, erosion, and sedimentation. The strengths of these interactions must be understood to best target limited management funds to achieve the desired management results.

Materials and Methods

Marine Sedimentation

The total sediment load on the Asan reef was estimated by dividing the fore reef slope into fifty compartments using ArcGIS (Figure 6-3). Compartments were created by drawing lines (approximately) perpendicular to the reef crest that transected the midpoint between sediment collector sites. The shallow edge of the 10 meter compartments followed the reef crest and the deep edge of the 20 meter compartment followed the 40 meter depth cline. Compartments at the edge of the study were extended to 150 m either east or west of the last trap. The deep and shallow water compartments were separated by a line drawn along the 15 meter depth cline. The area of reef within each compartment was computed using ArcGIS.

The total weight of terrestrial material measured at each site was computed by multiplying the total weight of sediment by the percent terrestrial (see Chapter 2). The total weight of the terrestrials sediment measured during each temporal replicate at each station (Chapter 2) was extrapolated to estimate the sediment collected over the entire compartment during each replicate Appendix 1). Data for one year (replicates 1-14) were summed to estimate the yearly sediment collection rate. If a value was missing for a site during a replicate, a zero value was used in the estimate. To determine sediment collected in the Asan sub-watershed, the six eastern and three western most sites

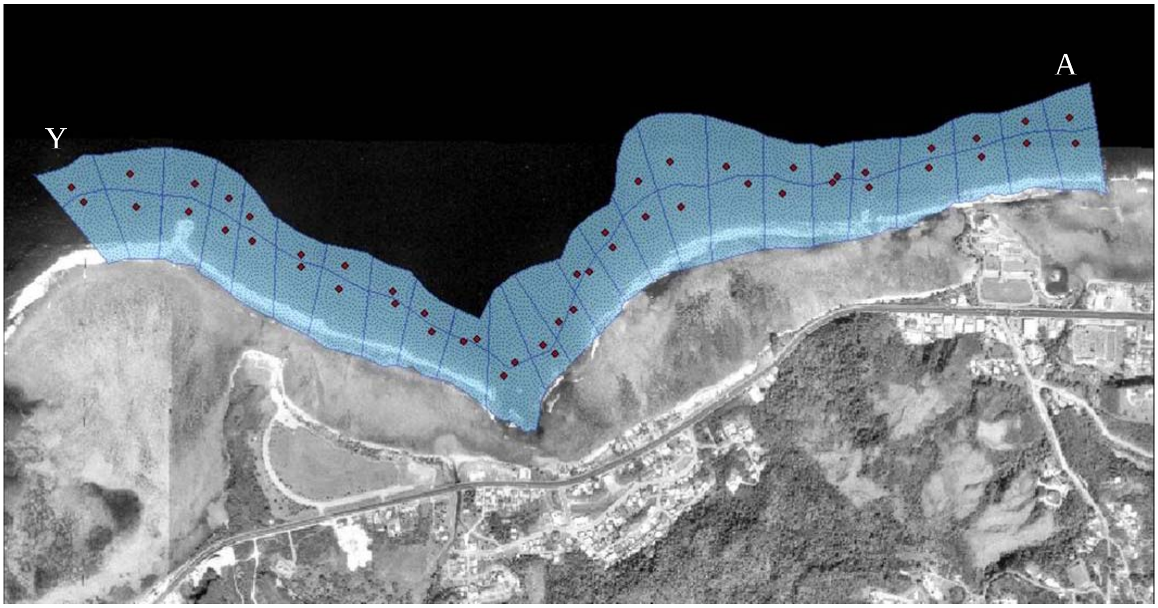

Figure 6-3. Reef compartments generated using ArcGIS to estimate total sediment load on the Asan fore reef. Dots are sediment collectors; letters are the site identifiers of the western most (Y) and eastern most (A) sediment collection sites. The sites are lettered alphabetically from right to left, but intervening site letters have been left off the figure for clarity (see Chapter 2).

(Location A, B, C, D, E, F & W, X, Y) were removed from the calculation. These sites were determined, based on the NRCS watershed delineations (CWAP 1998), to be outside of the Asan sub-watershed.

Sediment dynamics were modeled using the total weight of terrestrial sediment for all replicates. Stepwise linear regression techniques with five variables for rainfall quantity, three variables for rainfall intensity, and three spatial variables (Table 6-1) were used to generate a best fit sediment model. The best fit model was determined by highest r^2. Standardized residuals, Cook's distances, and leverages were examined to determine the model's overall fit.

Terrestrial Soil Loss

Total soil loss across the Asan sub-watershed was estimated by multiplying the average soil loss, in tonnes/ha, for each vegetation types buy the hectares of the vegetation type present in the sub-watershed. The number of hectares occupied by each vegetation type was calculating using ArcGIS and a vegetation habitat map obtained from the Guam Division of Forestry (Chapter 3; Table 3-4). Because the vegetation map did not differentiate savanna vegetation subtypes, an average soil loss of the mixed and fern subtypes was used in the calculations. For comparison, watershed level estimates of soil loss were also obtained using the available erosion data from the Fena (NRCS 2001). The Fena watershed estimate for soil loss in forested areas was used in all models. Limestone scrub and scrub forest categories were assumed to have the same soil loss rate of 1.8 tonnes/ha/year. Seasonal soil loss rates were incorporated into the calculations when possible.

A range of management scenarios were investigated, including: 1) no burning, no badlands; 2) 10% burning, no badlands; 3) no burning; 10% badlands; and 3) 10%

Table 6-1. Independent variables used in the sediment dynamics model.

Category	Term	Description
Rain Quantity	Rain	Total rainfall during replicate.
	Rain -1 day	Total rainfall starting 1 day before the replicate was deployed and ending 1 day before the replicate was collected.
	Rain -2 days	Total rainfall starting 2 days before the replicate was deployed and ending 2 days before the replicate was collected.
	Rain -3 days	Total rainfall starting 3 days before the replicate was deployed and ending 3 days before the replicate was collected.
	Rain -4 days	Total rainfall starting 4 days before the replicate was deployed and ending 4 days before the replicate was collected.
Rain Intensity	Days >2.5 cm	Number of days with more than 2.5 cm of rain.
	Days >5.0 cm	Number of days with more than 5.0 cm of rain.
	Days > 12.5 cm	Number of days with more than 12.5 cm of rain.
Spatial	Distance from Source	Linear distance from nearest point source to the sediment collector.
	Direction	Direction from nearest source. +1=up current; -1=down current
	Distance & Direction	Distance multiplied by Direction

burning and 10% badlands. The percentage values for burning and badlands were calculated as the hectares of savanna converted to either burned savanna or badland. A 10% conversion of savanna (10.6 hectares) equals approximately 2.9% of the total sub-watershed area. These estimates are intended to be realistic estimates of burned savanna and badland areas on southern Guam.

Results

Marine Sediment Collection

An estimated 36,000 tonnes/year of terrestrial sediment impact the fore reef slope within the study area. On the fore reef slope at the base of the Asan sub-watershed (excluding sites to the east and west of the watershed boundary), is impacted by approximately 25,200 tonnes/year of terrestrial sediment.

An initial best fit model was developed that included five significant terms (Table 6-2). All three spatial terms, Event>12.5 cm and Rain –3 days were all significant in the model. The model explained 52.7% of the variability in the data. Diagnostics showed that the model consistently underestimated sediment collection at site O-20. Further examination of this site found that its location was such that it collected more re-suspended material than other traps. The sediment collector at O-20 was at the base of the reef slope in a sandy patch, unlike all other collectors that were on hard substrate. For this reason, O-20 was excluded from the analysis.

When O-20 was excluded, only three terms remained in the best fit model (Table 6-2): Distance and Direction, Rain -3 days, and Events >12.5 cm. The model explains 56.2% of the variability in the data. Diagnostics showed that the fit of the model was improved, but the revised model consistently underestimated sediment collection during

Table 6-2. Significant terms and regression tables for the sediment collection model. Models are the result of a stepwise regression on sediment collection rates and using the terms in Table 6-1. Model 1 contains all sediment collection sites. Model 2 has had site O-20 removed. See text for full explanation.

Model 1

Term	Coefficient	St. Dev.	T	P
Constant	0.4433	0.1018	4.36	<0.001
Rain -3 days	0.45366	0.08555	5.30	<0.001
Events >12.5cm	0.22606	0.04999	4.52	<0.001
Dir.	0.42786	0.09706	4.41	<0.001
Dist.	-0.0006173	0.0001894	-3.26	<0.001
Dist. & Dir.	-0.0004670	0.0001893	-2.47	0.014

Source	DF	SS	MS	F	P
Regression	5	79.089	15.818	48.71	<0.001
Residual Error	634	205.868	0.325		
Total	639	284.956			

Model 2 (Site O-20 removed)

Term	Coefficient	St. Dev.	T	P
Constant	0.15043	0.02959	5.08	<0.001
Dist. & Dir.	0.00025479	0.00002602	9.79	<0.001
Events >12.5cm	0.23677	0.03753	6.31	<0.001
Rain -3 days	0.34442	0.06428	5.08	<0.001

Source	DF	SS	MS	F	P
Regression	3	51.742	17.247	96.14	<0.001
Residual Error	623	111.766	0.179		
Total	626	163.508			

replicate 12 (9 June – 8 July 2005). These date corresponded with the onset of the 2005 wet season, and during which a significant rain event occurred. Typhoon Tingting (June 27-28) deposited over 50 cm of rainfall in 24 hours (PEAC 2005), and was the largest single rainfall event of 2005.

Terrestrial Soil Loss

Using data obtained for this study, soil loss in the Asan sub-watershed was estimated at 2,531.5 tonnes/year (Table 6-3a). Using soil loss calculated in the Fena watershed, estimated soil loss in the Asan sub-watershed was approximately five times greater at 12,022.1 tonnes/year. Under this initial scenario, over 88.6% of the soil was lost off the savanna complex (including badlands).

Under the no burning-no badland scenario (Table 6-3b), erosion drops slightly (0.68%) relative to the initial IKONOS 2002 data estimates. The low incidence of badland in the original IKONOS 2002 data accounts for the small drop in soil loss. Under the 10% burning-no badlands scenario (Table 6-3c), erosion rises to 2,779.4 tonnes/year, a 9.8% increase. A smaller increase (2.1%) is observed if the Fena is used. Under the no burning-10% badland scenario (Table 6-3d), soil loss increases by 23.2% relative to the original IKONOS 2002 estimate. This rate of increase is lower than that

Table 6.3. Soil Loss (tonnes/year) under five separate scenarios for the Asan sub-watershed. Scenarios include: a) habitat area derived from 2002 IKONOS data (see Chapter 3); b) no burning-no badlands; c) 10% burning-no badlands; d) no burning-10% badlands; and e) 10% burning-10% badlands. Yearly soil loss rates for Fena Watershed were obtained from NRCS (2001). For the NPS estimate (this study), seasonal data for savanna, burned savanna and badlands were used where available. For other habitat types (e.g., scrub forest), Fena watershed estimates (NRCS 2001) were used.

a) IKONOS 2002		Soil Loss Rate (tonnes/ha)			Asan Soil Loss (tonnes/year)	
Habitat Type	**Hectares**	**Rain**	**Dry**	**Fena**	**NPS**	**Fena**
Scrub Forest	149.7	-	-	1.8	269.5	269.5
Limestone Scrub Forest	10.5	-	-	1.8	18.9	18.9
Savanna Complex	105.2	14.2	6.9	110.0	2,219.7	1,1572.0
Burned Savanna	0.0	35.3	10.8	146.0	0.0	0.0
Barren	0.3	43.9	34.2	539.0	23.4	161.7
Urban	96.4	?	?	?	0.0	0.0
	362.1				2,531.5	12,022.1

b) No burning-no badlands		Soil Loss Rate (tonnes/ha)			Asan Soil Loss (tonnes/year)	
Habitat Type	**Hectares**	**Rain**	**Dry**	**Fena**	**NPS**	**Fena**
Scrub Forest	149.7			1.8	269.5	269.5
Limestone Scrub Forest	10.5			1.8	18.9	18.9
Savanna Complex	105.5	14.2	6.9	110.0	2,226.1	11,605.0
Burned Savanna	0.0	35.3	10.8	146.0	0.0	0.0
Barren	0.0	43.9	34.2	539.0	0.0	0.0
Urban	96.4	?	?	?	0.0	0.0
	362.1				2,514.4	11,893.4

c) 10% burning-no badlands		Soil Loss Rate (tonnes/ha)			Asan Soil Loss (tonnes/year)	
Habitat Type	**Hectares**	**Rain**	**Dry**	**Fena**	**NPS**	**Fena**
Scrub Forest	149.7			1.8	269.5	269.5
Limestone Scrub Forest	10.5			1.8	18.9	18.9
Savanna Complex	94.9	14.2	6.9	110.0	2,002.4	10,439.0
Burned Savanna	10.6	35.3	10.8	146.0	488.7	1,547.6
Barren	0	43.9	34.2	539.0	0.0	0.0
Urban	96.4	?	?	?	0.0	0.0
	362.1				2,779.4	12,275.0

Table 6-3. (continued)

d) No burning-10% badlands Habitat Type	Hectares	Soil Loss Rate (tonnes/ha) Rain	 Dry	 Fena	Asan Soil Loss (tonnes/year) NPS	 Fena
Scrub Forest	149.7			1.8	269.5	269.5
Limestone Scrub Forest	10.5			1.8	18.9	18.9
Savanna Complex	94.9	14.2	6.9	110.0	2,002.4	10,439.0
Burned Savanna	0.0	35.3	10.8	146.0	0.0	0.0
Barren	10.6	43.9	34.2	539.0	827.9	5713.4
Urban	96.4	?	?	?	0.0	0.0
	362.1				3118.6	16440.8

e) 10% burning-10% badlands Habitat Type	Hectares	Soil Loss Rate (tonnes/ha) Rain	 Dry	 Fena	Asan Soil Loss (tonnes/year) NPS	 Fena
Scrub Forest	149.7			1.8	269.5	269.5
Limestone Scrub Forest	10.5			1.8	18.9	18.9
Savanna Complex	84.2	14.2	6.9	110.0	1,776.6	9,262.0
Burned Savanna	10.6	35.3	10.8	146.0	488.7	1,547.6
Barren	10.6	43.9	34.2	539.0	827.9	5,713.4
Urban	96.4	?	?	?	0.0	0.0
	362.1				3,381.5	16,811.4

observed using the calculations from the Fena watershed (36.8% increase). Under the final scenario, 10% burning-10% badland (Table 6-3e), a 33.6% increase in soil loss was observed. Once again, this is a lower percent increase than that observed when using the soil loss estimates from the Fena watershed (39.8%).

Discussion

Overall, there was poor agreement between the estimated sediment loads and upland soil loss for the Asan sub-watershed. The sediment load calculated for the Asan fore reef (25,200 tonnes/year) was nearly 10x the estimate calculated for upland erosion (2,531.5 tonnes/year). This discrepancy may be explained by the fact that the upland erosion rates measured in this work are minimum estimates. These rates were measured on low slop (9-12%) plots. Additionally, the upland erosion estimate does not account for burned savanna or urbanized areas, and does not contain the appropriate area of badland. If realistic estimates for the area of burned savanna and badlands are added to the soil loss estimate, it increases to 3,381.5 tonnes/year. This value is still only 13% of the marine terrestrial sediment load on Asan's nearshore reef slope.

The estimate including realistic burned savanna and badland areas (Table 6-2e) derived from the Fena watershed data (16,811.4 tonnes/year) is closer to the calculated sediment load. The Fena soil loss rates (NRCS 2001) were estimated using the RUSLE, and concerns about the appropriateness of this method on Guam have been raised. Schemen et al. (2002) found that RUSLE estimates were consistently higher than empirical estimates, raising serious questions about the applicability of the RUSLE method for Guam. In reality, erosion rates in the Asan sub-watershed are probably closer to those calculated using the soil loss measurements obtained in this study.

Reconciling the large difference between the soil loss and sediment collection on the reef is difficult. Our methods primarily measured sheet and rill erosion, which is believed to account for approximately 93% of the soil loss on Guam (NRCS 2001). However, significant streambank erosion has been observed on both major tributaries of the Asan River (Minton, pers. obs.) The contribution of this type of erosion to the coastal sediments is currently unknown.

No soil loss is available for the urban areas of Asan. Many of the homes and roads are cut into the hillside and may be producing significant erosion. Housing development on the west side of the Asan sub-watershed was also underway during this study, and the contractors were less than meticulous in maintaining appropriate sediment barriers around construction sites. It seems unlikely, however, that these activities could account for the 10-fold increase in soil loss need to reconcile with the calculated near shore sediment collection rates.

In all likelihood, a combination of these factors is probably accounts for the discrepancy. Soil loss over the range of slopes present in the watershed is higher than those reported here, and Streambank erosion and erosion off urban and construction sites also contribute to the watershed’s soil loss. These impacts need further investigation to quantify.

The best-fit sediment model provides interesting insight into the sedimentation dynamics on Asan reef. The model includes three predictors, one from each of the three variable categories: rainfall quantity, rainfall intensity, and spatial (Table 6-2b). The model shows that the distance and direction from the nearest point source is the best single predictor of sediment collection rates on the Asan fore reef slope. The inclusion of this specific spatial term suggests that non-point source runoff does not contribute significantly to sedimentation on Asan reef. This is supported by visual observations of sediment plumes originating from the Asan River and not along the length of the coast (Figure 6-4).

The model illustrates the importance of the rainfall intensity and quantity, with rainfall intensity having a higher significance. Daily rainfall events over 12.5cm (Events >12.5cm) were important predictors, suggesting that large events are a significant driver on this system. These large events are rare, with only two occurring in 2002 (July and December), one in 2003 (October), and three in 2004 (June (x2) and August). All of these events occurred during the wet season or at the start of the wet season (i.e., the end of June). Storm events of this magnitude are usually associated with tropical storms or cyclones and yearly variability in these storms is related to ENSO events (Guard et al. 1999).

The rainfall window offset by three days (Rain -3 days) proved to be the best rainfall quantity predictor, suggesting a three-day residence time of water in the watershed. This residence time is also certain to be a function of rain intensity. Following large storm events, flow at point sources rises significantly within a few hours of rainfall (USGS pers. comm.), as does the subsequent sediment discharge. Average

Figure 6-4. A sediment plume originates from the Asan River (lower left) following a large event in late June 2005 (replicate 12).

events (~0.75 cm/day), however, appear to move more slowly through the watershed (Minton pers. obs.).

The fit of the model was improved after removing site O-20 from the analysis. Diagnostics on the revised model revealed that it consistently underestimated the observed values in replicate 12 (9 June – 8 July 2004). This replicate occurred at the start of the 2004 wet season and had two large rain events (June 28-29) occur during it. The higher than predicted sediment collection values are interpreted as a sediment flushing event. During the dry season, rain events are small, usually <2.5cm, and total rainfall is low. This lack of rainfall quantity and intensity may not flush sediments entirely through the watershed. Instead sediments are probably transported into gullies and slow flowing streams were they collect over the course of the dry season. With the onset of the wet season, the quantity of rain fall and the intensity of events may be sufficient to flush these accumulated sediments onto the fore reef slope.

The timing of this flushing event is potentially problematic to coral reefs on Guam. The principal coral spawning season corresponds with the full moon during the months of June, July, and August (Richmond and Hunter 1990). Coral spawn and settling juveniles are susceptible to poor water quality (Richmond 1997; Gilmour 1999), including elevated sediment levels. Anthropogenically increased sediments loads could impact successful coral reproduction and/or recruitment to the reef, presenting a significant threat to the long term health and survival of Asan’s coral reefs. Coral recruitment rates are under active investigation by the National Park Service (Lundgren and Minton 2005) on the Asan fore reef slope, and preliminary data show low coral recruitment rates on the reef, but also no apparent correlation with sediment collection rates. Reasons for the lack of relationship between the coral settlement and sediment collection are currently unclear, but the research is ongoing (Lundgren and Minton 2005).

Upland erosion rates in Guam's savanna ecosystem are a result of the complex interaction of fire, vegetation and climate (Figure 6-5). Fire is a primary driver in tropical savanna ecosystems (D'Antonio and Vitousek 1992; Higgins et al. 2000; van Langevelde et al. 2003), and on Guam, is capable of altering plant species composition (Chapter 3). Changes in savanna vegetation affect erosion rates (Chapter 4). While sediment loss is occurring in vegetated savanna, erosion rates in burned and badland areas are six times higher than those observed in vegetated areas (Chapter 4). Following burning, invasive species, particularly grasses, tend to dominate the regenerating savanna, and these species appear to promote higher rates of soil loss than the mixed savanna community (Chapter 4). These invasive species alter the fire regime (Figure 6-5), increasing the fire frequency and intensity. The increased prevalence of burned savanna likewise increases the overall soil loss, altering the soil's physical and chemical properties (Chapter 5) and eventually exposing the underlying saprolite clays, which are highly acidic and have high concentrations of aluminum. These clay areas are incapable of supporting vegetation, and become badlands, which erode at a high rate (Chapter 4).

The mechanism that converts grasslands to badlands is still unclear, but may be related to declining soil quality associated with repeated burning and erosion. Repeated burning of tropical soils can increase the bulk density while lower pH, organic matter content (Wang et al.2003), and the cation exchange capacity (CEC) (Giovannini and Lucchesi 1997), which directly affects soil nutrient levels. Lower pH causes increased concentrations of saturated aluminum in the Akina soils that prevalent in the Asan sub-watershed (Young 1988). Burn also influences soil erodibility by producing microaggregates and particle that are more easily transported by rain splash (Ternan and Neller 1999). Increased erosion following burns degrades soil quality by removing topsoil, altering soil pH, lowering nutrients and organic material, altering texture and permeability, and lowering the cation exchange capacity (Lal 1995a, 1995b; Giovannini and Lucchesi 1997; Kaihura et al. 1999; Ternan and Neller 1999; Wang et al. 2003). Eventually, topsoil is removed exposed the underlying saprolite clays, which are incapable of supporting vegetation (Young 1988). Slumping of soils may also contribute to the formation of extensive badlands (Schemen et al. 2002), as water infiltrating the soils reaches the impermeable clays and "floats" the overlying soil layers causing them to slump.

Swordgrass (*Miscanthus floridulus*), which can form dense monotypic stands, is fire tolerant and capable of growing to three meters in height. Its presence on volcanic slopes (Stone 1970) suggests that it is more tolerant of acidic soils and elevated aluminum than mixed savanna species. Studies have shown *Miscanthus* is capable of growing under these harsh soil conditions (Wang et al. 2003). These features suggest a plausible mechanism allowing swordgrass to persist in Guam's savanna (Figure 6-5). As fire burns mixed savanna, soil erosion reduces soil quality and allows for exotic specie to invade. These species promote increase fire and, because of their bunch grass growth form, have a reduced capacity to hold soil, leading to further soil degradation. Eventually, swordgrass is able to invade, and because of its fire tolerance (Stone 1970), survive additional burning. Swordgrass sprouts quickly from its root crown following fire (Stone 1970) and can grow several meters tall in single season (GFD, pers. comm..). The dense monotypic stands are capable of shading other species, particular the shade intolerant exotic grass, such as Pennisetum polystachion (Ismail et al. 1994). Eventually

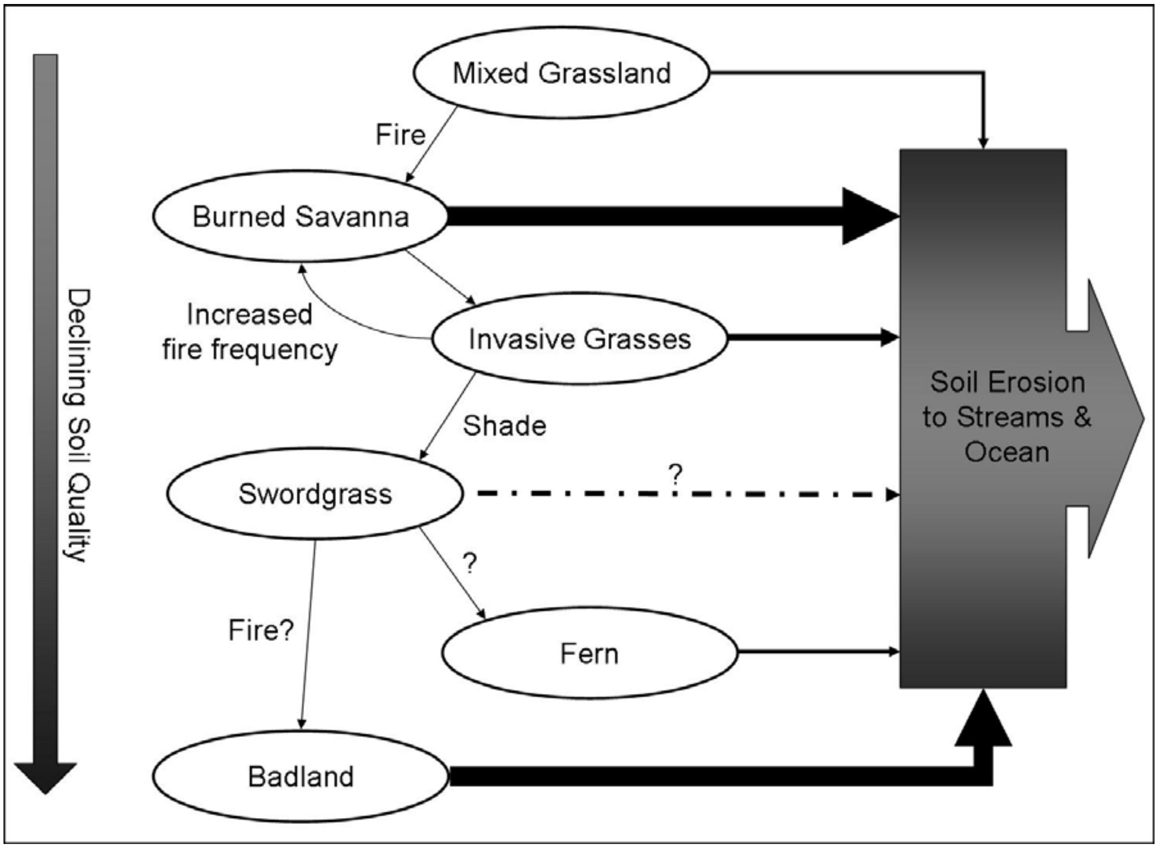

Figure 6-5. Schematic for fire-erosion-sedimentation cycle in the Asan sub-watershed. See text for an explanation. The thickness of the horizontal arrows represent the relative contribution to overall soil loss.

these grasses are excluded and replaced by a monotypic stand of swordgrass. Given that much of the erosion in southern Guam is the result of rill and sheet flow (NRCS 2001), swordgrass, a bunch grass characterized by large, widely spaced bunches, is probably less effective than mixed savanna at holding soils. Further erosion may eventually lead to badland formation (Figure 6-5).

Savannas in Asan exist as a vegetation mosaic (Chapter 3) that appears to be shifting toward vegetation states dominated by invasive species, swordgrass, and badland. As more mixed savanna is converted to other vegetation communities, upland erosion and coastal sedimentation will continue to increase.

Over 90% of the soil lost from the Asan sub-watershed comes off habitat associated with the savanna complex. Much of the eroded soil originates from vegetated savanna. Because of their relatively small area, badland complexes and burned savanna contribute less to watershed soil loss than vegetated savannas. The extensive cover of savanna on Guam is believed to be associated with anthropogenic fire (Athens and Ward 2004), and, prior to arrival of humans (sometime between 3,500-4,400 years ago), the island was probably heavily forested. As such, upland erosion rates and subsequent sedimentation rates on nearshore reefs could have been as low as 20% of the current estimated rates. Having evolved under these environmental conditions, it would not be surprising if Guam’s marine species were poorly adapted high erosion and sedimentation rates.

To reduce soil erosion and associated coastal sedimentation, three potential management actions could be taken in Asan's savannas: 1) remove fire; 2) restore badland areas; and 3) both remove fire and restore badland areas. While each of the three management actions would have positive effects on erosion, removing fire and restoring badlands would lower soil loss by approximately 25%. An active badland restoration program without a substantial effort to lower burning will lower soil loss by approximately 18%. Simply removing fire from the savanna without addressing the existing badland will lower soil loss by only 7-8%.

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Chapter 7.
Best Management Practices

Introduction

Because of its complexity, addressing Guam's erosion-sedimentation problem presents numerous challenges, including a lack of information and public understanding of the issues, and a shortage of financial resources. Coupled with local governmental apathy, these challenges make successfully mediating this significant environmental threat difficult. Any efforts to reduce erosion-sedimentation impacts need to be cognizant of the challenges, or success will be highly unlikely. This limits the strategies to relatively small-scale efforts that must mediate the most immediate and severe problems until public and government involvement can be increased. Until the seriousness of the environmental degradation and the magnitude of the problem is fully realized by the public and their elected representatives, long-term solutions to this problem will be unattainable.

This project has demonstrated that erosion and nearshore sediment loads are at a sufficiently high level to raise concerns for the long-term health and persistence of Guam's terrestrial savannas and its nearshore coral reefs ecosystems. Effective watershed management is the only way to achieve long-term reductions in these environmental impacts.

This chapter will propose several Best Management Practices (BMPs), weighing their overall environmental effectiveness, cost, likelihood of successful implementation given the cultural and political state of the island, and the time frame for success. Two categories of BMPs will be discussed: 1) those that address marine sedimentation; and 2) those that discuss upland erosion.

Materials and Methods

BMPs were brainstormed, developed, investigated, and ranked in five categories: 1) The level of environmental effect the BMP would have on reducing erosion or sedimentation; 2) the cost of implementing and maintaining the BMP; 3) the technical difficulty in implementing the BMP; 4) the local political will to support the BMP; and 5) the public will to support the BMP. All categories were ranked as low, medium, or high. Based on the rankings in the five categories, an overall score could be developed to suggest a possible priority ranking for implementation.

Results and Discussion

Guam is a developing island territory, and as such has often placed its environmental health behind its economic growth. Since the 1980s tourism has become the primary economic force on the island, with over 1 million tourists visiting each year. To stay competitive in the tourism market, however, requires continued "improvements" to distinguish Guam from other tropical Pacific Islands. In the drive to improve Guam as a "product," environmental concerns often become of secondary importance. This was especially true during the Asian recession in the 1990s, when fewer Asian citizens were traveling, and Guam found itself competing for tourism dollars with other tropical destinations such as Hawaii, the Commonwealth of the Northern Mariana Islands (e.g. Saipan), Palau, Indonesia, and southeast Asia. As a result, the general political mindset on the island has drifted away from environmental stewardship and toward market forces.

The public's understanding of Guam's environmental issues is also limited. The environmental issues facing Guam are complex, and the composition of Guam's population raises unique challenges. Guam has many citizens from other Pacific islands, many of who do not speak English as their first language and who were raised with a different environmental ethic.

Educating lawmakers and the general public about Guam's environment and the impact of humans is the most important need for the island. Without education, many of the proposed BMPs will not have the political or public support necessary for them to succeed.

Sedimentation BMPs

The only way to fully address Asan's coastal sedimentation issue is to reduce soil erosion and/or soil transport. Any BMP that does not directly reduce soil erosion must be considered a short-term, stopgap measure. The data from this study suggest that Asan's coral reefs evolved under sediment conditions that were 20% of their current load. The ability to achieve this level of success is minimal given the current conditions of the watershed. To return to these pre-human sediment levels, all of the Asan sub-watershed would need to be converted to forest, a state that is unlikely to happen. The landscape, due to centuries of human activity may no longer be able to support the pre-human environment. Therefore, the goal of managers should be to reduce sediment inputs as much as possible, and a combination of actions that reduce upland erosion and divert sediment that is being transported to the ocean will be necessary. Reducing upland erosion is discussed in the next section. Diverting sediment can be accomplished with two types of BMPs: 1) those that trap and remove sediments and 2) those that slow the flow or reduce the amount of water moving through the watershed.

The sediment dynamic model developed in Chapter 6 provides guidance for developing tenable BMPs. BMPs to mediate sediment transport should focus on Asan's primary point sources, including the Asan River and the drainage pipe along Route 1 on the eastern edge of the watershed. Efforts should be of a suitable magnitude and timed so that their greatest effect occurs at the start of the wet season, when sediment load are at their highest. Ten BMPs (Table 7-1) were developed to address sedimentation issues in the Asan watershed. These could easily be generalized to other locations on Guam.

Education about coral reefs and sediment impacts ranked as the number two BMP. Success with this BMP is necessary to achieve success with many of the other BMPs, which ranked low primarily because of the lack of public and political will (i.e., ponding basins, green roofing, etc.), which is directly correlated with their understanding of the issues and threats.

Not surprisingly, BMPs that would have the largest environmental effect (e.g. sediment basins, ponding basins) also required the greatest monetary investment. The structures require considerable engineer expertise, would most likely necessitate the

Table 7-1. BMPs to reduce sedimentation on Asan's coral reefs. All BMPs have been ranked as a High, Medium, or Low for environmental effectiveness, cost, difficulty to install and maintain, political will to support, and public will to support. Total score is derived from assigning a rank to each of the five categories as follows: For the Environmental effectiveness, Political will to support, and Public will to support H=5, M=3, and L=1; For Cost and Difficulty to install and maintain H=1, M=3, and L=5**.**

BMP	**What it is/What it does**	**Environ. Effect**	**Cost**	**Difficulty**	**Political Will**	**Public Will**	**Total Score**
Rainwater Catchment	Installing catchment systems on all buildings in Asan would capture storm water before it entered streams and other drainages. Because of the watershed's steep terrain, land runoff could b captured in a large municipal tank for use as an emergency water supply. This has the additional benefit of providing water to the village.	M	L	L	M	H	21
Sedimentation Education	Educate the public on the impacts of sedimentation on Guam's coral reefs. Use education to highlight the environmental damage in a meaningful way to the public (e.g., declining coral reef impacts on fisheries) teach about ways to reduce runoff and sedimentation.	M	M	H	L	L	17
Permeable surfaces	All paved surfaces could be replaced with permeable materials or re-paved using techniques that enhance permeability. This would slow runoff water in urban areas and reduce laminar sheet flow. Less water would enter the drainage system	M	M to H	L	M	M	15-17
Install Asan River Sediment Basin	A sediment basin at the mouth of the Asan River would slow water movement and collect sediment. Basin would need continual maintenance dredging that should be conducted at the end of the dry season. Finding a suitable area to create the basin might be problematic.	H	H	M	M	L to M	13-15
Re-channel storm drainage on Rte. 1	The drainage system on Rte 1 near Adelup Pt. should be re-designed so that water does not cascade down the cliff and directly into the ocean. Water should be channeled in a permeable canal to a sediment basin. Basin would need continual maintenance dredging that should be conducted at the end of the dry season.	L	M to H	L to M	M	M	11-15

Table 7-1. (continued)

BMP	What it is/What it does	Environ. Effect	Cost	Difficulty	Political Will	Public Will	Total Score
Green Roof	Installing environmentally friendly green roofs slow runoff waters in urban areas and reduces laminar sheet flow. Less water enters the drainage system from Asan Village	L	L to M	L	L	L	11-13
Ponding basins	Ponding basins are essentially sediment basins but they would be installed at various locations within the watershed, where ever topography is appropriate. These slow the movement and collect sediments. These would require maintenance dredging	H	H	M	L	L to M	11-13
Remove impermeable channels	Rip-rap and concrete lined drainage ditches should be replaced with permeable (e.g., green) surfaces. Storm drains should be replaces with green filters systems to slow the transport of rainwater. Systems should be developed to be effective with large storm events	M	H	H	L	L	9
Create wanders in Asan River to slow water flow	Engineer additional bends in the Asan River to slow water movement and allow sediment to settle before reaching ocean. Needs to be used in combination with the sediment basin which would need continual maintenance dredging that should be conducted at the end of the dry season.	M	H	H	L	L	9

acquisition of private land, and would require continued, probably yearly, maintenance. In the island's current economic state, these BMPs are unlikely to occur.

Erosion BMPs

This research has shown that addressing erosion rates in badland areas can reduce the watershed sediment loss by as much as 17% and that by restoring badlands and stopping anthropogenic fire, the soil loss rates can be reduced by 25% (Chapter 6).

Several techniques exist to address badland erosion, but few viable long-term options exist for War in the Pacific NHP. While short-term solutions, such as coconut fiber mats and anti-erosion cloth, have been used in the past by other agencies, but the National Park Service and the island are seeking a long-term solution to badland erosion. The Guam Division of Forestry is currently undertaking a large forest restoration project focused in the Ugum watershed. However, their use of invasive exotic *Acacia* trees runs counter to the ideals of the National Park Service, which would rather see native vegetation returned to the park's and the island's badland areas. While GFD has had some success transforming the exotic *Acacia*s to native forest, the results of their efforts will not be known for many years. The National Park Service will endeavor to develop a more appropriate long-term solution that fits better with its mission.

Without addressing the ultimate causes of badlands, long-term solutions will remain illusive. This project has shown that wildland fire contributes to increased soil erosion and may be responsible for savanna conversion to badland. While other factors (e.g. soil characteristics, mass wasting events, etc.) contribute to badland formation and/or increased erosion, wildland fire is an anthropogenic disturbance that can be addressed. However, this highlights the importance in having viable, affordable options to restore badland areas when they development by natural mechanism.

Reducing anthropogenic fire on Guam will be a long and difficult process. Fire has become an integral part of the local culture, particularly among game hunters, and while local laws exists criminalizing wildland arson (9 GCA §34.20), fire use has not slowed. Enforcement and prosecution are sporadic at best.

While the widespread application of fire is probably the most significant, chronic anthropogenic impact in Asan – and will be the focus of these BMPs – other anthropogenic activities, including off-road vehicle use and poor construction practices, also contribute to soil erosion and should be addressed. Eleven BMPs (Table 7-2) were developed to address fire and erosion issues in the Asan watershed. These BMPs could be generalized to other locations on Guam.

Once again education ranked out as one of the top priority BMPs. Successfully implementing this BMP is crucial to the success of other BMPs. Several enforcement BMPs ranked high. Guam has many environmental regulations in place, but these are poorly enforced primarily because of the lack of political will and funding for a sufficient number of appropriately trained enforcement officers. On Guam, enforcement fails at many levels, but most significantly, failure occurs at the prosecutorial and judicial level. Environmental crimes are not considered as important as other crimes and are often not prosecuted or are dismissed. This attitude can only change with education.

Table 7-2. BMPs to reduce erosion and soil loss in the Asan sub-watershed. All BMPs have been ranked as a High, Medium, or Low for environmental effectiveness, cost, difficulty to install and maintain, political will to support, and public will to support. Total score is derived from assigning a rank to each of the five categories as follows: For the Environmental effectiveness, Political will to support, and Public will to support H=5, M=3, and L=1; For Cost and Difficulty to install and maintain H=1, M=3, and L=5.

BMP	**What it is/What it does**	**Environ. Effect**	**Cost**	**Difficulty**	**Political Will**	**Public Will**	**Total Score**
Fire Education	Educate on the impacts of fire, highlighting the environmental damage in a way meaningful to the public and lawmakers. This may convince the public to stop setting fires, to support other BMPs, or to seek legal action against those that burn. Eliminating all fires would lower erosion by ~7%.	M	M	H	L	L	17
Reforestation	Convert badlands to forest. GFD is currently attempting this in the Ugum watershed. This is a long-term project. Converting to Acacia trees is not a viable option for the National Park. Restoration of all badlands in the Asan sub-watershed would lower soil loss by ~18%. This is a long-term solution to badland erosion.	H	M	M	M	M	17
Enforcement of construction Regulations	Developer and contractors are required to use environmentally sound practices, such installation of sediment fences. These regulations are often ignored and are poorly enforced. Enforcement to ensure compliance would reduce erosion associated with construction sites.	L	L	L	L	H	17
Restore Burned Savanna	Using well-established, fire rehabilitation techniques, burned areas can be treated to reduce erosion rates and restore vegetation. While not a long-term solution to burning, this BMP would lower erosion rates associated with the burned savanna.	M	M	L	L	H	17
Coconut fiber/Erosion cloth	Install erosion cloth over burned and badland areas to reduce soil erosion. This technique has been used with limited success to reduce erosion in the Fena Watershed. This is not a long-term solution to badland erosion	L	L	L	L to M	L to M	13-17

Figure 7-2. (continued)

BMP	What it is/What it does	Environ. Effect	Cost	Difficulty	Political Will	Public Will	Total Score
No wet season building	Erosion is highest during the wet season. Activities that remove vegetation or break ground should not be permitted to occur during the wet season. Construction permits should not be issued for any project that disturbs soil with a start between June and December.	L to M	L	L	L	L to M	13-17
Put out all fires	All fires will be aggressively pursued and extinguished. This will reduce the area of burned savanna and lower watershed soil loss by ~7%.	M	L	L	L to M	H	11-13
Ponding basins	Ponding basins are essentially sediment basins installed at various locations within the watershed – where ever topography is appropriate. These slow water movement and reduce the likelihood of stream bank erosion.	H	H	M	L	L to M	11-13
Install Anti-erosion Vegetation	Revegetate badlands with anti-erosion plants such as vetiver grass. Restoration of all badlands in the Asan sub-watershed would lower soil loss by ~18%. This may be a long-term solution to badland erosion.	M	M	M	L	L	11
Ban Off-Road Vehicles/Enforce	Off road vehicles contribute to erosion by destroying vegetation. Restricting the use o off road vehicles to appropriate areas would reduce their environmental impacts. Off-roading is not a significant issue in the Asan sub-watershed but it is in other areas.	L	M	M	L	L to M	9-11
Badland Restoration	Convert badlands to native savanna vegetation. Methods do not currently exist. Restoration of all badlands in the Asan sub-watershed would lower soil loss by ~18%. This is a long-term solution to badland erosion	M	M to H	H	L	L	7-9

Appendix 1.
Estimated Sediment Loads

Appendix 1. Estimated sediment loads (tonnes) over one year (14 replicates) for the fore reef slope in Asan. The watershed estimate is for the fore reef slope within the Asan sub-watershed (Sites G-V). See Chapter 6 for a discussion of the methods used to arrive at these estimates.

Site		Rep. missing	Compartment Area (m^2)	Terrestrial Sediments (tonnes)
A	10 m	7	28508.2	502.4
	20 m	2	20611.1	410.6
B	10 m	3	28845.6	1100.3
	20 m	3	13189.9	558.2
C	10 m	7	26903.4	147.8
	20 m	4	16414.7	162.4
D	10 m	3	35202.3	2573.3
	20 m	2	16335.5	286.7
E	10 m	2	28911.4	2256.0
	20 m	2	17420.5	191.6
F	10 m	7	23812.7	847.4
	20 m	2	15636.5	396.1
G	10 m	4	34293.6	505.8
	20 m	2	20491.1	243.1
H	10 m	5	43596.7	288.7
	20 m	4	31692.9	259.6
I	10 m	9	34404.3	53.2
	20 m	5	46535.2	319.8
J	10 m	6	29361.7	650.1
	20 m	3	24581.4	474.6
K	10 m	5	24806.5	503.2
	20 m	2	13366.3	187.8
L	10 m	6	21453.9	690.9
	20 m	1	13047.5	634.9
M	10 m	1	15358.2	1642.5
	20 m	2	26286.4	2428.4
N	10 m	3	9977.2	892.8
	20 m	0	20060.1	1581.8

Appendix 1. (continued)

Site		Rep. missing	Compartment Area (m^2)	Terrestrial Sediments (tonnes)
O	10 m	1	33726.0	3242.2
	20 m	2	21724.1	6344.3
P	10 m	7	24612.7	108.6
	20 m	2	11491.5	793.7
Q	10 m	2	22676.8	331.4
	20 m	3	12751.3	487.1
R	10 m	2	27384.1	553.0
	20 m	3	15283.4	240.5
S	10 m	1	38430.0	604.1
	20 m	0	15056.4	145.3
T	10 m	0	30626.8	271.0
	20 m	1	13560.5	135.8
U	10 m	2	31632.2	267.3
	20 m	2	13305.0	99.2
V	10 m	10	23893.0	37.3
	20 m	2	15209.5	202.9
W	10 m	7	30591.6	174.5
	20 m	2	24606.4	222.1
X	10 m	4	19787.4	220.7
	20 m	2	27428.3	205.8
Y	10 m	1	26777.3	267.5
	20 m	1	30107.9	336.4
Total			1191767.1	36080.7
Watershed			760676.4	25220.8

Appendix 2.
Status of Plants

Appendix 2. The status of plants observed in vegetation plots, including notes on their known synonyms, taxonomy, and origin.

SCIENTIFIC NAME	SYNONYMS	ORGIN	FAMILY	HABIT
Pennisetum polystachion	*Pennisetum setosum, Cenchrus setosus* *Panicum polystachion, Panicum polystachion*	Tropical Africa to India now rather commonly introduced in warm regions	Poaceae	Grass
Bothriochloa bladhii	*Andropogon bladhii , A. intermedius, Andropogon haenkei, Andropogon glaber, Bothriochloa caucasica, B. intermedia, B. haenkei, B. glabra, B. glabra* ssp. Haenkei *Dichanthium intermedium,*	Tropical Africa through India to China and Australia.	Poaceae	Grass
Chromolaena odorata	*Eupatorium odoratum*	Tropical America, but common in many tropical regions as a weed	Asteraceae	Shrub
Hyptis capitata	N/A	Central America from southern Mexico to Panama, now widespread as a weed.	Lamiaceae	Herb
Rhynchospora rubra	*Schoenus ruber, R. wallichiana*	Tropical America, Indomalaysia, S. Japan, and the Pacific, incl. N. Australia	Cyperaceae	Herb
Curculigo orchioides		Native. Widely distributed from India to Malaysia	Hypoxidaceae	Herb
Elephantopus mollis	*E. scaber*	Native of Tropical America	Asteraceae	Herb
Passiflora foetida	*Passiflora edulis*	Native of Tropical America now a pantropical weed	Passifloraceae	Vine
Dicranopteris linearis	*Gleichenia linearis*	Indigenous; pantropical	Gleicheniaceae	Fern
Ipomea littoralis	*I. denticulata, I. choisyana, I. gracilis*	Malaysia, Pacific: *I. gracilis* according to Fosberg confined to N. Australia	Convolvulaceae	Vine
Ipomoea triloba	*I. mariannensis*	Native of Tropical America	Convolvulaceae	Vine

Appendix 2. (continued)

SCIENTIFIC NAME	**SYNONYMS**	**ORGIN**	**FAMILY**	**HABIT**
Fimbristylis dichotoma	*Scirpus dichotomus, F. diphyll:* Over 400 synonyms	Pantropical, and in many warm temperate regions.	Cyperaceae	Herb
Fimbristylis tristachya	*F. mariana, F. maxima, F. marianna* *F. schoenoides* var. *foenea*	Malaysia, Australia	Cyperaceae	Herb
Scleria polycarpa	*S. margaritifera*	Malaysia, N. Australia, Polynesia	Cyperaceae	Herb
Dimeria chloridiformis	*Andropogon chloridiformis, Haplanchne pilosissima, Dimeria pilosissima*	Endemic	Poaceae	Grass
Paspalum orbiculare	*Paspalum scrobiculatum* var. *obiculare* *Paspalum cartilagineum*	Malaysia to Polynesia. Possibly native in Guam	Poaceae	Grass
Sporobolous fertilis	*Agrostis fertilis, Agrostis indica, Sporobolus elongatus, Sporobolus indicus*	Native of Austronesia (Australia to Malaya, part of Polynesia)	Poaceae	Grass
Lindsea ensifolia	N/A	Indigenous; paleotropical	Pteridaceae	Fern
Casuarina equisetifolia	*Casuarina litorea* L. var. *litorea, Casuarina littorea*	Australia and into Melanesia Micronesia and Polynesia Probably an ancient introduction to Polynesia Either native to Melanesia and Micronesia or an early introduction.	Casuarinaceae	Tree
Glochidion marianum	*Phyllanthus gaudichaudii* M.A. var. *marianus*	Endemic	Euphorbiaceae	Shrub
Alysicarpus vaginalis	*A. nummularifolius*	Tropics of the Old World, now adventive in many tropical countries	Fabaceae	Herb
Crotalaria retusa	N/A	Uncertain, possibly Asiatic orgin	Fabaceae	Herb
Leucaena leucocephala	*Leucaena glauca*	Tropical America, but through introductions now virtually pan-tropical. Widely planted and seeded in Micronesia.	Fabaceae	Tree
Mimosa pudica		First described from Brazil, now a pan-tropical weed.	Fabaceae	Herb
Flagellaria indica	N/A	Paleotropics	Flagellariaceae	Vine

Appendix 2. (continued)

SCIENTIFIC NAME	**SYNONYMS**	**ORGIN**	**FAMILY**	**HABIT**
Psidum guajava	N/A	Native of Tropical America	Mytraceae	Tree
Arundina graminifolia			Orchidiaceae	
Polygala paniculata	N/A	Panpaleotropical; Possibly native in Guam	Polygalaceae	Herb
Morinda citrifolia	N/A	Widespread & Native, or often planted throughout Tropical Asia & Pacific	Rubiaceae	Tree
Lygodium microphyllum				
Waltheria indica L.	N/A	Pantropical Weed.	Sterculiaceae	Fern
Stachytarpheta jamaicensis	*Stachytarpheta indica*	Tropical American, now pantropical, weed/	Verbenaceae	Herb

Appendix 3.
Plant Checklist

Appendix 3. Checklist of plants found in all vegetation plots.

	Grass-1	Grass-2	Grass-3	Grass-4	Bad-1	Bad-2	Bad-3
AMARYLLIDACEAE							
Curculigo orchioides Gaertn.	X	X	X				
ASTERACEAE							
Chromolaena odorata (L.) King & H.E. Robins		X	X				
Elephantopus mollis Kunth			X				
PASSIFLORACEAE							
Passiflora foetida L.							
GLEICHENIACEAE							
Dicranopteris linearis (Burm.) Underwood					X		
CONVOLVULACEAE							
Ipomoea littoralis Blume	X		X				
Ipomoea triloba L.							
CYPERACEAE							
Fimbristylis dichotoma (L.) Vahl	X	X					
Fimbristylis tristachya R.Br.	X	X	X				
Rhyncospora ruba Domin.		X	X				
Scleria polycarpa Boeck.	X	X		X			

Appendix 3. (continued)

	Grass-1	Grass-2	Grass-3	Grass-4	Bad-1	Bad-2	Bad-3
POACEAE							
Dicanthium bladhii (Retz.) Clayton		X	X	X			X
Dimeria chloridiformis (Gaud.)K. Schum. & Lauterb.		X	X		X	X	X
Pennisetum polystachion (L.) J.A. Schultes	X	X	X	X			X
Paspalum orbiculare	X						
Sporobolous fertilis	X	X	X	X			
Lindsea ensifolia		X	X				
CASUARINACEAE							
Casuarina equisetifolia L.			X				
EUPHORBIACEAE							
Glocidion marianum Mueller-Arg., L.	X						
FABACEAE							
Alysicarpus vaginalis (L.) D.C.				X			
Crotalaria retusa	X						
Leucaena leucocephala (Lam.) deWit				X			
Mimosa pudica L.							
FLAGELLARIACEAE							
Flagellaria indica L.							
LAMNIACEAE							
Hyptis capitata Jacq.	X	X	X	X			
MYRTACEAE							
Psidum guajava L.				X			

Appendix 3. (continued)

	Grass-1	Grass-2	Grass-3	Grass-4	Bad-1	Bad-2	Bad-3
ORCHIDACEAE							
Arundina graminifolia (D.Don) Hochr.	X	X	X				
POLYGALACEAE							
Polygala paniculata (L.) J.A. Schultz	X	X	X				X
PASSIFLORACEAE							
Passiflora foetida L.				X			
RUBIACEAE							
Morinda citrifolia L.							X
SCHIZIACEAE							
Lygodium microphyllum		X					
STERCULIACEAE							
Waltheria indica L.			X	X			
VERBENACEAE				X			
Stachytarpheta jamaicensis (L.) Vahl	X		X	X			

Appendix 3. (continued)

	Fern-1	Fern-2	Fern-3	Fern-4	Burn-1	Burn-2	Burn-3
AMARYLLIDACEAE							
Curculigo orchioides Gaertn.							
ASTERACEAE							
Chromolaena odorata (L.) King & H.E. Robins							
Elephantopus mollis Kunth							X
PASSIFLORACEAE							
Passiflora foetida L.							
GLEICHENIACEAE							
Dicranopteris linearis (Burm.) Underwood	X	X	X	X			
CONVOLVULACEAE							
Ipomoea littoralis Blume							
Ipomoea triloba L.							
CYPERACEAE							
Fimbristylis dichotoma (L.) Vahl					X	X	X
Fimbristylis tristachya R.Br.	X			X	X		X
Rhyncospora ruba Domin.				X			
Scleria polycarpa Boeck.					X	X	

Appendix 3. (continued)

	Fern-1	Fern-2	Fern-3	Fern-4	Burn-1	Burn-2	Burn-3
POACEAE							
Dicanthium bladhii (Retz.) Clayton					X	X	X
Dimeria chloridiformis (Gaud.)K. Schum. & Lauterb.	X		X				
Pennisetum polystachion (L.) J.A. Schultes	X	X	X	X	X		X
Paspalum orbiculare					X		
Sporobolous fertilis							X
Lindsea ensifolia							
CASUARINACEAE							
Casuarina equisetifolia L.				X			
EUPHORBIACEAE							
Glocidion marianum Mueller-Arg., L.			X				
FABACEAE							
Alysicarpus vaginalis (L.) D.C.						X	X
Crotalaria retusa							X
Leucaena leucocephala (Lam.) deWit							
Mimosa pudica L.						X	
FLAGELLARIACEAE							
Flagellaria indica L.		X					
LAMNIACEAE							
Hyptis capitata Jacq.				X	X	X	X
MYRTACEAE							
Psidum guajava L.							

Appendix 3. (continued)

	Fern-1	Fern-2	Fern-3	Fern-4	Burn-1	Burn-2	Burn-3
ORCHIDACEAE							
Arundina graminifolia (D.Don) Hochr.	X	X	X	X			
POLYGALACEAE							
Polygala paniculata (L.) J.A. Schultz						X	
PASSIFLORACEAE							
Passiflora foetida L.						X	X
RUBIACEAE							
Morinda citrifolia L.							
SCHIZIACEAE							
Lygodium microphyllum		X					
STERCULIACEAE							
Waltheria indica L.				X		X	
VERBENACEAE							
Stachytarpheta jamaicensis (L.) Vahl		X		X	X	X	X

Appendix 4.
Plant Biomass

Appendix 4. Plant biomass of all species collected in vegetation plots. Two quadrats (A & B) were collected for each vegetation plot. Data is expressed as g/m^2.

Species	**Native**	**Grass 1A**	**Grass1B**	**Grass2A**	**Grass 2B**
Centosteca lappacea	yes	40.67	38.73	46.21	0.00
Dichanthium bladhii	no	400.00	380.95	0.00	0.00
Dimeria chioridiformis	yes	0.00	0.00	923.81	538.10
Pennisetum polystachion	no	1123.81	1070.29	0.00	0.00
POACEAE #1	?	0.00	0.00	10.29	16.64
POACEAE #2	?	0.00	0.00	29.24	17.30
CYPERACEAE	?	0.00	0.00	0.00	0.00
Fimbristylis dichotoma	no	8.29	7.89	0.00	0.00
Fimbristylis tristachya	no	0.00	0.00	219.05	723.81
Rhyncospora ruba	no	0.00	0.00	814.29	0.00
Alysicarpus vanginalis	no	0.00	0.00	0.00	6.19
Chromalena odorata	no	0.00	0.00	0.00	0.00
Curculigo orchioides	yes	0.00	0.00	1.27	0.86
Hyptis capitata	no	9.51	9.06	9.05	20.67
Mimosa pudica	no	0.00	0.00	0.00	0.00
Stachytarpheta jamaicensis	yes	4.10	3.90	7.90	5.78
Timonius mollis	yes	0.00	0.00	0.00	0.00
Waltheria indica	yes	0.00	0.00	0.00	0.00
Arudina graminifolia	no	51.14	48.71	1.43	0.00
Cassytha filiformis	no	0.00	0.00	0.00	0.00
Dicranopteris linearis	yes	0.00	0.00	0.00	0.00
Lindsaea ensifolia	yes	0.00	0.00	0.00	0.00
TOTAL WEIGHT		**1637.51**	**1559.54**	**2062.52**	**1329.33**
SPECIES PRESENT		**7**	**7**	**10**	**8**

Veg Type	**Grass 1A**	**Grass1B**	**Grass2A**	**Grass 2B**
Native	44.76	42.63	979.19	544.73
Non-native	1584.47	1509.02	10.48	26.86
Unknown	8.29	7.89	1072.86	757.74

Appendix 4. (continued)

Species	**Native**	**Grass 3A**	**Grass 3B**	**Grass 4A**	**Grass 4B**
Centosteca lappacea	yes	0.00	0.00	0.00	0.00
Dichanthium bladhii	no	80.00	24.76	224.76	229.52
Dimeria chioridiformis	yes	3.81	47.62	0.00	0.00
Pennisetum polystachion	no	119.05	7.62	0.00	0.00
POACEAE #1	?	64.76	29.52	0.00	0.00
POACEAE #2	?	0.00	18.10	0.00	0.00
CYPERACEAE	?	160.00	40.00	0.00	0.00
Fimbristylis dichotoma	no	0.00	0.00	0.00	0.00
Fimbristylis tristachya	no	0.00	0.00	0.00	0.00
Rhyncospora ruba	no	0.00	0.00	0.00	0.00
Alysicarpus vanginalis	no	0.00	0.00	0.00	6.67
Chromalena odorata	no	0.00	0.00	0.00	0.00
Curculigo orchioides	yes	0.00	0.00	0.00	0.00
Hyptis capitata	no	20.95	0.00	0.00	0.00
Mimosa pudica	no	0.00	0.00	0.00	0.00
Stachytarpheta jamaicensis	yes	0.00	0.00	0.00	89.52
Timonius mollis	yes	0.00	0.00	0.00	0.00
Waltheria indica	yes	0.00	0.00	0.00	3.81
Arudina graminifolia	no	0.00	0.00	0.00	0.00
Cassytha filiformis	no	0.00	0.00	0.00	0.00
Dicranopteris linearis	yes	0.00	0.00	0.00	0.00
Lindsaea ensifolia	yes	0.00	0.00	0.00	0.00
TOTAL WEIGHT		**448.57**	**167.62**	**224.76**	**329.52**
SPECIES PRESENT		**6**	**6**	**1**	**4**

Veg Type	**Grass 3A**	**Grass 3B**	**Grass 4A**	**Grass 4B**
Native	3.81	47.62	0.00	93.33
Non-native	220.00	32.38	224.76	236.19
Unknown	224.76	87.62	0.00	0.00

Appendix 4. (continued)

Species	Native	Burn 1A	Burn 1B	Burn 2A	Burn 2B
Centosteca lappacea	yes	0.00	0.00	0.00	0.00
Dichanthium bladhii	no	300.95	182.86	204.76	180.95
Dimeria chioridiformis	yes	0.00	0.00	0.00	0.00
Pennisetum polystachion	no	53.33	0.00	0.00	0.00
POACEAE #1	?	0.00	0.00	3.81	1.90
POACEAE #2	?	0.00	0.00	0.00	0.00
CYPERACEAE	?	0.00	0.00	647.62	51.43
Fimbristylis dichotoma	no	0.00	0.00	0.00	0.00
Fimbristylis tristachya	no	0.00	0.00	0.00	0.00
Rhyncospora ruba	no	0.00	0.00	0.00	0.00
Alysicarpus vanginalis	no	0.00	0.00	0.00	0.00
Chromalena odorata	no	0.00	0.00	0.00	0.00
Curculigo orchioides	yes	0.00	0.00	0.00	0.00
Hyptis capitata	no	9.52	2.86	9.52	12.38
Mimosa pudica	no	0.00	0.00	0.00	0.00
Stachytarpheta jamaicensis	yes	0.95	0.95	0.00	0.00
Timonius mollis	yes	0.00	0.00	0.00	0.00
Waltheria indica	yes	0.00	0.00	0.00	0.00
Arudina graminifolia	no	0.00	0.00	0.00	0.00
Cassytha filiformis	no	0.00	0.00	0.00	0.00
Dicranopteris linearis	yes	0.00	0.00	0.00	0.00
Lindsaea ensifolia	yes	0.00	0.00	0.00	0.00
TOTAL WEIGHT		**364.76**	**186.67**	**865.71**	**246.67**
SPECIES PRESENT		**4**	**3**	**4**	**4**

Veg Type	Burn 1A	Burn 1B	Burn 2A	Burn 2B
Native	0.95	0.95	0.00	0.00
Non-native	363.81	185.71	214.29	193.33
Unknown	0.00	0.00	651.43	53.33

Appendix 4. (continued)

Species	Native	Burn 3A	Burn 3B
Centosteca lappacea	yes	97.14	61.90
Dichanthium bladhii	no	447.62	628.57
Dimeria chioridiformis	yes	0.00	0.00
Pennisetum polystachion	no	0.00	0.00
POACEAE #1	?	2.98	0.00
POACEAE #2	?	0.00	0.00
CYPERACEAE	?	0.00	0.00
Fimbristylis dichotoma	no	5.14	9.01
Fimbristylis tristachya	no	0.00	0.00
Rhyncospora ruba	no	0.00	0.00
Alysicarpus vanginalis	no	0.95	1.14
Chromalena odorata	no	0.95	1.71
Curculigo orchioides	yes	1.25	0.00
Hyptis capitata	no	409.52	219.05
Mimosa pudica	no	0.00	0.00
Stachytarpheta jamaicensis	yes	0.00	0.00
Timonius mollis	yes	0.00	0.00
Waltheria indica	yes	0.00	0.00
Arudina graminifolia	no	0.00	0.00
Cassytha filiformis	no	0.00	0.00
Dicranopteris linearis	yes	0.00	0.00
Lindsaea ensifolia	yes	0.00	0.00
TOTAL WEIGHT		**965.56**	**921.39**
SPECIES PRESENT		**8**	**6**

Veg Type	Burn 3A	Burn 3B
Native	98.39	61.90
Non-native	858.10	848.76
Unknown	9.08	10.72

Appendix 4. (continued)

Species	Native	Fern 1A	Fern 1B	Fern 2A	Fern 2B
Centosteca lappacea	yes	0.00	0.00	0.00	0.00
Dichanthium bladhii	no	0.00	0.00	0.00	0.00
Dimeria chioridiformis	yes	0.00	0.00	0.00	0.00
Pennisetum polystachion	no	0.00	0.00	0.00	0.00
POACEAE #1	?	0.00	0.00	0.00	0.00
POACEAE #2	?	0.00	0.00	0.00	0.00
CYPERACEAE	?	0.00	0.00	0.00	0.00
Fimbristylis dichotoma	no	0.00	0.00	0.00	0.00
Fimbristylis tristachya	no	0.00	0.00	0.00	0.00
Rhyncospora ruba	no	0.00	0.00	0.00	0.00
Alysicarpus vanginalis	no	0.00	0.00	0.00	0.00
Chromalena odorata	no	0.00	0.00	0.00	0.00
Curculigo orchioides	yes	0.00	0.00	0.00	0.00
Hyptis capitata	no	0.00	0.00	0.00	0.00
Mimosa pudica	no	0.00	0.00	0.00	0.00
Stachytarpheta jamaicensis	yes	0.00	0.00	0.00	0.00
Timonius mollis	yes	0.00	0.00	0.00	0.00
Waltheria indica	yes	0.00	0.00	0.00	0.00
Arudina graminifolia	no	0.00	0.00	0.00	0.00
Cassytha filiformis	no	0.00	0.00	0.00	0.00
Dicranopteris linearis	yes	1145.71	881.90	1052.38	57.14
Lindsaea ensifolia	yes	0.00	0.00	0.00	0.00
TOTAL WEIGHT		**1145.71**	**881.90**	**1052.38**	**57.14**
SPECIES PRESENT		**1**	**1**	**1**	**1**

Veg Type	Fern 1A	Fern 1B	Fern 2A	Fern 2B
Native	1145.71	881.90	1052.38	57.14
Non-native	0.00	0.00	0.00	0.00
Unknown	0.00	0.00	0.00	0.00

Appendix 4. (continued)

Species	Native	Fern 3A	Fern 3B	Fern 4A	Fern 4B
Centosteca lappacea	yes	0.00	0.00	0.00	0.00
Dichanthium bladhii	no	0.00	0.00	0.00	0.00
Dimeria chioridiformis	yes	0.00	0.00	0.00	3.71
Pennisetum polystachion	no	0.00	0.00	24.48	0.00
POACEAE #1	?	0.00	0.00	0.00	0.00
POACEAE #2	?	0.00	0.00	0.00	0.00
CYPERACEAE	?	0.00	0.00	2.10	148.38
Fimbristylis dichotoma	no	0.00	0.00	0.00	0.00
Fimbristylis tristachya	no	0.00	0.00	0.00	0.00
Rhyncospora ruba	no	0.00	0.00	0.00	0.00
Alysicarpus vanginalis	no	0.00	0.00	0.00	0.00
Chromalena odorata	no	0.00	0.00	0.00	0.00
Curculigo orchioides	yes	0.00	0.00	0.00	0.00
Hyptis capitata	no	0.00	0.00	0.00	0.00
Mimosa pudica	no	0.00	0.00	0.00	0.00
Stachytarpheta jamaicensis	yes	0.00	0.00	4.89	2.19
Timonius mollis	yes	0.00	552.38	0.00	0.00
Waltheria indica	yes	0.00	0.00	0.00	0.00
Arudina graminifolia	no	0.00	0.00	0.00	0.00
Cassytha filiformis	no	0.00	0.00	1.62	2.19
Dicranopteris linearis	yes	1076.19	619.05	1095.24	923.81
Lindsaea ensifolia	yes	0.00	0.00	1.90	13.69
TOTAL WEIGHT		**1076.19**	**1171.43**	**1130.22**	**1093.97**
SPECIES PRESENT		**1**	**2**	**6**	**6**

Veg Type	Fern 3A	Fern 3B	Fern 4A	Fern 4B
Native	1076.19	1171.43	1102.03	943.40
Non-native	0.00	0.00	26.10	2.19
Unknown	0.00	0.00	2.10	148.38