Watershed restoration as a tool for improving coral reef resilience against climate change and other human impacts

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Highlights

- Erosion control techniques were tested as watershed restoration strategies
- A soil probing method for measuring soil depth was developed
- The total sediment trapped on land through erosion control was determined
- We suggest how to use the tools to reduce sedimentation impacts on Fouha Bay coral reefs and elsewhere

Keywords: watershed; watershed restoration; coral reefs; sedimentation; Guam

Abstract

Environmental stressors in coastal areas threaten the sustainability of marine resources and reduce their resilience to climate change impacts. Accelerated land erosion is a major stressor that leads to increased turbidity and sedimentation on downstream coral reefs and the degradation of ecosystem functions. Volunteers from a community-based initiative in Guam installed 130 tree seedlings and 54 m of sediment filter socks in eroding hillsides above Fouha Bay, to reduce erosion. A soil probing method for measuring soil depth was developed and used to evaluate the effectiveness of the watershed restoration tools. The trees and socks trapped 111.8 tons of sediment on land after 21 months. In heavily eroding portions of the restoration plot, where socks and trees were used in combination, the mean sediment trapping efficiency was 44 kg m^{-2} yr^{-1}. Previous studies indicate a 75% reduction in sedimentation rate is required to bring Fouha Bay below severe-catastrophic sedimentation stress (>50 mg cm^{-2} day^{-1}). Based on the observed sediment trapping efficiency of restoration tools in this study, an estimated 0.05 km^2 of severely eroding hillsides must be treated with 19 km of socks and 11,000 trees to trap 2,121 tons of sediment and achieve the necessary reduction. If sediment input into the bay is controlled, existing sediment will clear out with storm-driven swells. As shown in other high islands, coral reefs are resilient and can recover after sedimentation stress is reduced. Data generated on the efficiency of watershed restoration tools in this study can be used in watershed management plans to promote the sustainability and resilience of coastal areas in other tropical islands.

Introduction

Climate change is a clear and present threat to coastal areas in tropical islands, causing increased storm surges, coastal flooding, mass coral bleaching, sea level rise, and diminished food security (Keener et al., 2012; IPCC, 2014). Anthropogenic stressors decrease the social-ecological resilience of coastal regions to recover from large disturbances, which are occurring more frequently due to climate change (Adger et al., 2005). Human-induced environmental stressors in marine systems include overfishing, pollution, and eutrophication from land-based nutrient and sediment input (McCook et al., 2007). In order to ensure the resilience and sustainability of future coasts, both global and local level solutions are necessary.

This research used a community-based approach to reduce the environmental stressor, accelerated terrestrial erosion. This stressor results in the loss of agricultural lands (Pimentel, 1987), a decline in downstream coastal water quality, and diminished health and resilience of coral reefs (Bellwood et al., 2004; Fabricius, 2005). This study took place in the eroding hillsides of the La Sa Fu'a Watershed, Guam. It evaluated the effectiveness of trees and sediment filter socks as watershed restoration tools aimed at decreasing accelerated erosion and subsequent sediment loading onto downstream coral reefs.

Poorly executed road construction, wildland arson, uprooting of vegetation by feral ungulates, and irresponsible usage of recreational off-road vehicles accelerate rates of terrestrial erosion in Guam (Burdick et al. 2008). Human impacts can create extensive areas of unprotected soil that allow normal levels of rainfall to cause higher rates of erosion, removing rich topsoil and preventing most vegetation from reestablishing (El-Swaify, 1982). Areas of volcanic soils exposed through erosion are referred to as badlands (Kottemair et al., 2011).

On small islands, land-based pollutants need only travel short distances via stormwater runoff to reach the ocean and harm coral reefs (Richmond et al., 2007). In Guam, runoff of sediment is a major problem for central and southern coastal coral reefs (Birkeland et al., 2000). Sediment stresses corals and often kills them in two primary ways; 1) suspension of sediment leading to high turbidity of coastal waters as a result of sediment loading from runoff sources and later resuspension by waves, and 2) the direct deposition of particulate sediment onto corals, known as sedimentation (Fabricius, 2005; Bartley et al., 2014). Increased turbidity, especially by clay and fine silt particles, reduces the availability of *photosynthetically active radiation* (PAR), the form of light zooxanthellae converts to energy for coral as part of their symbiosis (Fabricius et al., 2014). Sedimentation of terrestrial organic-rich particles onto corals increases microbial respiration, which leads to anoxia, reduced pH, production of hydrogen sulfide, the bacterial decomposition of coral tissue, and coral mortality (Weber et al., 2012).

Coral reefs with high sediment input typically have fewer coral species, less live coral cover, slower growth rates, reduced coral recruitment, decreased calcification, decreased net productivity, and lower reef accretion rates (Rogers, 1990). Excessive sediment can also interfere with reproduction and recruitment of corals (Richmond, 1997). In one study, for example, a thin layer of deposited fine terrigenous sediment 0.9 mg cm^{-2} thick, was found to completely block coral recruitment (Perez et al., 2014).

Background of study site

In Fouha Bay, the outlet of the La Sa Fu'a Watershed, coral cover, colony size, richness, and diversity increase in the offshore direction as the sedimentation rate decreases (Randall and Birkeland, 1978; Rongo, 2004; and Minton, 2015). Wolanski et al. (2003) studied the flooding and sedimentation dynamics in Fouha Bay, providing the following background information. There are an estimated 10 rain events each wet season during which the La Sa Fu'a River floods for a period of 10 hours, discharging sediment-laden water in pulses into Fouha. Once the sediment-laden discharge enters the bay, it passively floats along the surface in a 1 m thick plume. Almost immediately, the sediment in the plume begins to settle on the substratum as individual particles or as part of aggregates of marine snow. Suspended sediment concentration (SSC) exceeds 1,000 mg l^{-1} when the La Sa Fu'a River floods due to rain events and again when storm driven swells re-suspend sediment. The latter cause can last several days. Although storm-driven swells increase turbidity, the wave action is important for flushing sediment out of the bay.

Minton (2015) conducted a Moving Window Analysis (West and Van Woesik, 2001) in Fouha Bay. His study provided sediment threshold information for certain taxa, which act as key descriptive species indicating shifts in assemblages. For example, the first coral, *Leptastrea purpurea*, was not observed until 34 m from the shoreline at a sedimentation rate of 100 mg cm^{-2} day^{-1}. The threshold information is important for understanding ecological changes that may occur as restoration efforts continue and sedimentation in Fouha Bay is reduced. Findings of Minton (2015) aligned with the degrees of sedimentation impact proposed in Pastorok and Bilyard (1985).

Watershed management and erosion control are the recommended recovery action when high sediment input is the main environmental stressor affecting a coral reef (Richmond, 2005). Land-based remediation is an effective means of reducing anthropogenic disturbance and returning pre-impact conditions to allow natural coral recovery (Richmond, 2005; Zimmer, 2006; Jokiel et al., 2006). Past studies in the La Sa Fu'a Watershed identified degraded environmental conditions and articulated the need for management action in the area (Randall and Birkeland, 1978; Richmond, 1993; Scheman et al., 2003; Wolanski et al., 2003; Wolanski et al., 2004; Richmond et al., 2004; Rongo, 2004). Wolanski et al. (2004) concluded that Fouha Bay is capable of recovering healthy fish habitat and productivity if land-based remediation efforts are carried out successfully.

Community initiative

A community initiative called the Humåtak Project (humatakproject.org) coordinated the watershed restoration activities evaluated in this study. The initiative formed in 2001 after community members became concerned about the diminishing quality of nearshore marine resources, which resulted from poorly executed road construction between 1988 and 1990 (Richmond, 1993).

Materials and methods

Tree plantings

Acacia auriculiformes, *Acacia confusa*, and *Acacia mangium* are the main tree species propagated for watershed restoration in Guam. The trees are fast growing and able to thrive in infertile badland soils due to the presence of nitrogen-fixing bacteria present in their roots. Acacias act as "nurse" plants, allowing other species of plants to grow after facilitating improvements in soil quality (Yang et al., 2009). Over time, acacias improve soil quality by increasing water absorption, regulating temperature through canopy shading, adding organic matter through leaf litter, and increasing nutrient content. Although these acacia trees are exotic (non-native) species to the island, there have been no signs of invasiveness in Guam (Space and

Falanruw, 1999). Along with *Acacia auriculiformes*, three native tree species were used for reforestation efforts in the La Sa Fu'a Watershed; *Artocarpus mariannensis*, *Premna obtusifolia*, and *Calophyllum inophyllum*.

Sediment filter socks

Sediment filter socks, also known as compost filter socks, are mesh stockings filled with compost or mulch that remove pollutants, such as sediment or particulate nutrients, from stormwater runoff (Archuleta and Faucette, 2011). The devices are placed perpendicular to the flow of water. Stormwater runoff is restricted as it flows through the sock resulting in the trapping and deposition of sediment, both behind and inside the sock. This process promotes revegetation in badland areas. Sediment filter socks were shown to remove 65% of clay and 66% of silt particulates in a USDA study (Faucette et al., 2009). The devices are commonly used to manage stormwater around construction sites in Hawaii and some U.S. mainland states. Sediment filter socks are advantageous to silt screens because the devices allow faster filtering of runoff, less ponding of water, and less risk of collapse during large storm events. Also, unlike silt screens, sediment filter socks do not require the digging of trenches during installation.

Restoration test plot

Tree seedlings used in this study were propagated in planting tubes (656 ml volume) with Sun Gro® Sunshine Mix® potting soil, typically to heights between 0.3 m and 1 m tall. Filtrexx® 8 in diameter Durasoxx HD™ sediment filter socks were threaded onto 8 in diameter cylindrical polyvinylchloride (PVC) plastic pipes and mulch was pushed through the pipe with wooden plungers to fill the socks. Tree seedling and sock installation took place in June 2012 during the transition into the annual wet season to ensure water availability for seedling establishment.

The restoration test plot was located at 60 m elevation in the mid portion of the La Sa Fu'a Watershed (Figure 1). The treated plot area was 1.77 x 10^3 m^2. The total plot area including upslope drainage was 5.50 x 10^3 m^2. The site was chosen for its badland characteristics, accessibility for volunteers, and proximity to the La Sa Fu'a River (15 m at closest point). Pedestal, sheet, and gully erosion were observed prior to restoration treatments. The plot was divided into four sections; Tree Plot (TP), Sediment Sock Plot (SP), Tree Reference Plot (TR), and Sediment Sock Reference Plot (SR).

The TP hillside had a 20% slope and 90% average ground cover with 1.2 m average vegetation height. The bottom of the hillside bordered the La Sa Fu'a River. Following technical consultation from the US Department of Agriculture Natural Resources Conservation Service Pacific Islands Area Office and protocols described in NAVFAC (2010), 92 tree seedlings, 0.3m to 1m tall, were planted in 12 staggered rows spaced 3 m apart. In each row, trees were planted 3 to 5 m apart from the stem centers. Tree species were alternated between rows. Rows were composed of either all native species (*Artocarpus mariannensis*, *Premna obtusifolia*, or *Calophyllum inophyllum*) or all acacia species (*Acacia auriculiformes*, *Acacia confusa*, and *Acacia mangium*). The TR plot had a 31% slope with similar ground cover and soil as TP. TR was a few meters East of TP, separated by an eroding gully.

A badland area of the restoration test plot containing less than 25% ground cover was designated as Sediment Sock Plot (SP). SP was treated with a combination of sediment filter socks and tree seedlings. 54 m of sediment filter socks were installed in 17 segments, each 3 to 5.4 m in length. Acacia tree seedlings were interspersed between the sediment filter socks.

Casurina equisetifolia seeds were scattered into and behind the sediment filter socks. One portion of badland soils was left untreated to be observed as a reference (SR).

Sediment accumulation

Twenty-one months after tree seedlings and sediment filter socks were installed, soil depth data were collected to determine their sediment trapping efficiency. Stainless steel soil probes were used to measure soil depth. The mass of total sediment accumulation was calculated by multiplying the volume of accumulated soil and the bulk density of the soil determined from on-site samples using a USDA (2001) protocol.

In TP, transects were laid at 11 of the 12 tree rows. Six 1 m x 1 m quadrats were placed along each transect, 3 behind a randomly selected tree (if present in the row), and 3 in a randomly selected open space. In each quadrat, the soil was probed using consistent pressure in 3 haphazardly selected square grids and measurements were averaged. In TR, data was collected in the same manner, except quadrats were laid in six randomly selected open spaces since trees were not planted there.

In SP, 3 to 4 transects were laid every 1 m on the uphill side of each of the sediment filter sock segments still present after 21 months. Two sock segments out of the original 15 were not found because they either degraded or were hidden in the vegetation. Transect lengths were dependent on the length of the socks, which ranged from 3 to 5.4 m. Soil depth measurements were collected in every square meter along the transects using 1 m x 1 m quadrats and a soil probe (Figure 2). Data in SR were collected in the same manner across five 3 m wide transects.

Photos were taken at the restoration test plot every few months to create a time-series record of restoration progress.

Statistical analyses

Data were statistically analyzed using GraphPad PRISM® Version 5.0b. The soil depth measurements in TP and TR were evaluated using an unpaired t-test. Soil depth measurements collected uphill of the sediment filter socks and at SR were evaluated using a One-way ANOVA. A Tukey Post Hoc Test was used to compare the mean soil depth of each sock to the mean soil depth of the SR. Parallel transects were placed at 1, 2, and 3 m distances behind each sediment filter sock. The mean soil depth of Transect 1 across all socks was compared to that at Transects 2 and 3 using a One-way ANOVA and Tukey Post Hoc Test.

Results

Tree Plot (TP) sediment accumulation

The mean soil depth at TP was 14.5 cm and 10.0 cm at TR (Figure 3). The difference in mean soil depth between the plots indicated 4.5 cm of sediment accumulation in the TP site. A t-test indicated the difference was extremely significant ($P<0.0001$, $t=6.6$, $df=5.426$). Over the 1652 m^2 area of the tree plot, the accumulation yielded a mass of 104.8 metric tons based on a bulk density of 1410 kg m^{-3} calculated from onsite soil samples (Equation 1, Table 1). There was no significant difference between TP soil depth measurements taken directly behind trees and those taken in open spaces. However, soil depth measurements behind trees were significantly greater than soil depth measurements taken in TR ($P<0.0001$, $t=6.606$, $df=83$) (Figure 4).

Equation 1: Sediment accumulation equation for Tree Plot (TP)

$$[((T - R) * a)] (b) = Mass\ of\ Sediment\ Accumulated\ (kg)$$

T= Mean soil depth of TP (m)

R= Mean soil depth of TR (m)

a= Area of TP (m^2)

b= Mean bulk density of TP soil (1410 kg m^{-3})

Sock Plot (SP) sediment accumulation

Soil depth measured behind sediment filter socks was significantly greater than soil depth at SR ($P<0.0001$, $F=16$, $df=123$) (Figure 5). Soil depth measurements were used to determine the soil accumulation in each square meter of the SP. Based on the volume of accumulated sediment and the bulk density of on-site soil, 7.03 metric tons was the total mass of soil accumulated (Equation 2 and Table 2).

<u>Equation 2 Sediment accumulation equation for each m^2 in the Sock Plot (SP)</u>

$$[((A + B + C)/3 - r) (l \bullet w))] \bullet (b) = Mass\ of\ Sediment\ Accumulated\ (kg)$$

A= soil depth measurement 1 (m)

B= soil depth measurement 2 (m)

C= soil depth measurement 3 (m)

r= reference plot mean depth, constant (0.035 m)

l= Length of quadrat, constant (1 m)

w= width of quadrat, constant (1 m)

b= mean bulk density of soil in SP, constant (1410 kg m^{-3})

Field measurements uphill of sediment filter socks revealed that at least $115m^2$ of soil surface was influenced by the presence of the socks. The majority of sediment typically collected directly behind the uphill side of the socks and tapered off with increasing distance from the socks (Figure 6). The mean soil depth of transects across all socks was compared. Soil depth decreased with increasing distance from socks ($P<0.02$, $F=4.367$, $df=38$) (Figure 7).

Tree health and survival

The tree seedlings in TP were observed 21 months after planting (Figure 8). Their health was characterized based on height, foliage color and density, and thickness of branches and trunk. *Acacia auriculiformes* trees were 2 m to 6 m in height. The largest and most robust acacias in TP were those planted closest to the river. The growth of uphill acacia trees appeared stunted. There was evidence of deer rub scarring on tree barks. The native species grew less than 1 m. 13.6% of native species and 69.7% of acacias planted had survived (Table 3). There may be more surviving native trees hidden in tall grass and unaccounted for. None of the *Casurina equisetifolia* seeds that were scattered in and behind the uphill side of sediment filter socks germinated. Acacia trees in SP displayed stronger health indicators than TP acacias. The SR trees had thick layers of leaf litter under their canopies, flowering branches, and tree seedlings sprouting (Figure 9). Some trees grew to 8 m.

Soil profile observations

A soil profile was removed from the ground in SP to verify soil depth measurements collected with the soil probe (Figure 10). The top 15 cm in the profile represents accumulated soil and detritus that deposited behind the sock. The soil profile displays a discontinuity at 15 cm depth and a shift to hardpan soil, or the pre-existing soil base. The 15 cm of accumulation was consistent with soil depth measurements using a soil probe in the same area.

Discussion

Sediment trapping

The significant difference between the sediment depth measured at TP and SP and their respective reference plots indicate that the trees and sediment filter socks are effective watershed restoration tools for reducing soil erosion. Although the slope was steeper in TR than TP (20% vs 31%), other variables such as elevation and size were consistent in the field experiment across natural terrain. At TP, there was no significant difference in soil depth measurements collected next to trees and those collected in open spaces. This suggests that the presence of trees influences soil beyond the area directly under their canopies (Figure 4).

Tree health

The trees that displayed the healthiest characteristics 21 months after planting were the acacias in SP. The trees were planted in an actively eroding badland area where high rates of water runoff flowed through the site during rain events. The sediment filter socks decreased runoff velocity in the treatment area allowing water to pool near the seedlings and absorb into the ground. If left unmediated without sediment filter socks, the stormwater runoff may have washed the tree seedlings away before they had a chance to establish.

Casuarina equistifolia seed cones did not germinate, likely due to being picked and scattered while green and immature. However, SP would likely have experienced overcrowding issues with the acacia trees if the *Casuarina equistifolia* plantings were successful. If tested in a future restoration plot, brown cones on the verge of releasing seeds should be picked.

In TP, 14% of the native trees survived after 21 months compared to 70% of acacia trees. Nitrogen-fixing bacteria are present in the root systems of acacia trees allowing them to thrive in low nutrient environments (Yang et al., 2009). Nutrient availability in TP limited the success of native tree species. Quarterly fertilizer applications and weeding are recommended for future restoration plots where there is ground cover vegetation. Native trees should not be planted in badland areas until after acacias or other vegetation are successful in improving soil quality over time. Healthier trees at the bottom of TP is consistent with other studies showing higher productivity of soils at the bottom of a hillsides due to erosion processes moving enriched top soil downslope (Verity and Anderson, 1990). Spacing of 3-5m between trees was sufficient to prevent overcrowding of trees.

Feral ungulates

Feral ungulates undermined the effectiveness of the watershed restoration treatments, but did not completely destroy any trees or sediment filter socks. Ungulate tracks were found throughout the restoration and reference plots. Ground cover vegetation was absent along their tracks. Pig scat was found under the trees, likely because of the shade provided by the canopies. Scarring on trees in the uphill portion of TP is a sign of deer rubbing.

It is recommended that future partnerships be formed with hunters from the village to develop an ungulate management plan to remove ungulates from the restoration sites. Such a plan could include allowing the use of dogs, setting up baiting stations, trapping, or hiring a contractor to eradicate ungulates. A depredation permit can be issued to those hunters from local agencies to lift seasonal and bag limit restrictions specifically for restoration sites. Installation of ungulate exclusion fencing is also a recommended action to keep pigs and deer out of restoration plots, but it is a more costly solution.

Restoring Fouha Bay

Based on the sediment load decay model developed in Rongo (2004), Fouha Bay receives a sediment yield of 1,714 tons yr^{-1}. Minton (2015) determined that a 75% reduction in the sedimentation rate would be necessary to bring all of Fouha Bay below the severe-catastrophic sedimentation degree of impact (>50 mg cm^{-2} day^{-1}) proposed in Pastorok and Bilyard (1985). Assuming sedimentation rate correlates with sediment yield, a sediment-input reduction of 1,379 tons would be required.

The sediment delivery ratio (SDR) is the proportion of gross eroded sediment in a catchment basin that reaches an outlet site (SDR= sediment yield / gross erosion) (El Swaify et al., 1982; Walling, 1983). Only a fraction of gross erosion reaches a watershed outlet because there are a series of sediment sources and sinks along the path of sediment transport. Using a conservative SDR of 0.65 from the lower range of SDRs determined for other Guam watersheds (Hanson et al. 2007; NAVFAC, 2010), trapping 2,121 tons of sediment on land would be required to achieve the sediment yield reduction recommended in Minton (2015).

The total sediment trapped in the restoration test plot was 111.8 tons. The highest trapping efficiency of sediment filter socks and acacia trees (two trees per 9 m^2) observed in this study was 44 kg m^{-2} yr^{-1}. Therefore, the necessary sediment yield reduction can be achieved by treating a total area of 0.05 km^2 with 19 km of 8 in diameter sediment filter socks and 11,000 acacia tree seedlings.

If sediment input into Fouha Bay is controlled, existing sediment may clear out under natural conditions. Wolanski et al. (2003) estimated the residence time of sediment in Fouha Bay is 4.3 years and that it would take 30 days of storm-driven swells to flush out all existing deposited sediment.

There are examples of coral recovery after a reduction of sedimentation stress. In the Pilaa area of Kauai, Hawaii, illegal land clearing smothered and killed coral colonies in 2001. After a series of large storm waves flushed sediment off reefs over the next three years, the number of coral colonies doubled (Jokiel and Brown, 2004). Coral health also improved in Kaho`olawe, Hawai`i after the removal of over 25,000 goats (Jokiel et al., 1995), and in Airai Bay, Palau after a moratorium was placed on the clearing of mangroves (Richmond et al., 2007).

However, according to Minton (2015), it is unclear whether Fouha Bay has undergone a coral to algal-dominated system phase shift during its years of degradation since the poorly executed road construction in the 1980s (Richmond, 1993). Minton (2015), Wolanski et al. (2003) and Rongo (2004) all describe mats of algae present in Fouha Bay that are trapping sediment. Although the Fouha studies did not quantify the amount of sediment trapped directly in algal mats, macroalgae on a reef in Molokai, Hawaii was found to trap 54 g m^{-2} of sediment (Stamski and Field, 2006). Field et al. (2007) suggests that sediment particles trapped in macroalgae remain affixed until the algae decays.

In the case that sediment does not clear out after sediment input to the bay is controlled, algae can be removed to promote the flushing of sediment. In Maunalua Bay, Hawaii, 1.32×10^6 kg of the invasive algae *Avrainvillea amadelpha* was removed by hand from 11 ha of reef flat over a 15-month period to release trapped sediment (Kittinger et al., 2013). Algal removal has led to the clearing of sediment and decreased its residence time in the bay (Macduff, 2011).

Fish abundance in Fouha Bay was already depleted from extractive practices before the expansion of the Agat-Umatac Road (1988-1990) caused chronic habitat loss. If watershed restoration efforts eventually reduce sedimentation stress in Fouha Bay and the reef habitat becomes suitable for fishery recruitment, the next phase of the Humåtak Project may require the implementation of additional fisheries regulations in order to revive sustainable reef fish populations for village residents. Due to the interest in environmental issues and the current level of community engagement in Humåtak, community-based fisheries management strategies discussed in Loerzel (2013) and Zanre (2014) would be appropriate to consider for the enhancement of fish populations in Fouha Bay. Including a particular focus on increasing herbivorous fish populations may simultaneously increase fish biomass and help reduce algal mats through grazing, promoting the flushing of trapped sediment and further improvement of coral reef habitat. The Kahekili Herbivorous Fisheries Management Area, established in Maui by the State of Hawai`i in an effort to control the overabundance of marine algae (Friedlander et al., 2012), may be used as a model to enhance herbivorous fish populations.

Conclusions

This research demonstrates tree seedlings and sediment filter socks are effective coastal watershed management tools that can be used to promote the resilience and sustainability of future coasts. Trees stabilize soil, increase water absorption, and improve soil quality. Sediment filter socks decrease stormwater runoff velocity, filter out loose sediment from the runoff, and promote water absorption into soil. These two watershed restoration tools are effective options to promote the revegetation of eroding hillsides and reduce the transport of loose sediment downstream through a watershed.

Trees and sediment filter socks accumulated a total of 111.8 metric tons of sediment in the restoration test plot. The highest rate of sediment accumulation was observed in the Sock Plot (SP) where a combination of trees and sediment filter socks were used to treat a badland area (Table 3.2: Socks 12 to 15). The average sediment accumulation in that area was 44 kg m^{-2} yr^{-1}. It is recommended that similar badland areas be prioritized for restoration in future watershed management strategies and mitigation plans. Sediment filter socks and trees should be used together as erosion treatments as they are most effective in combination.

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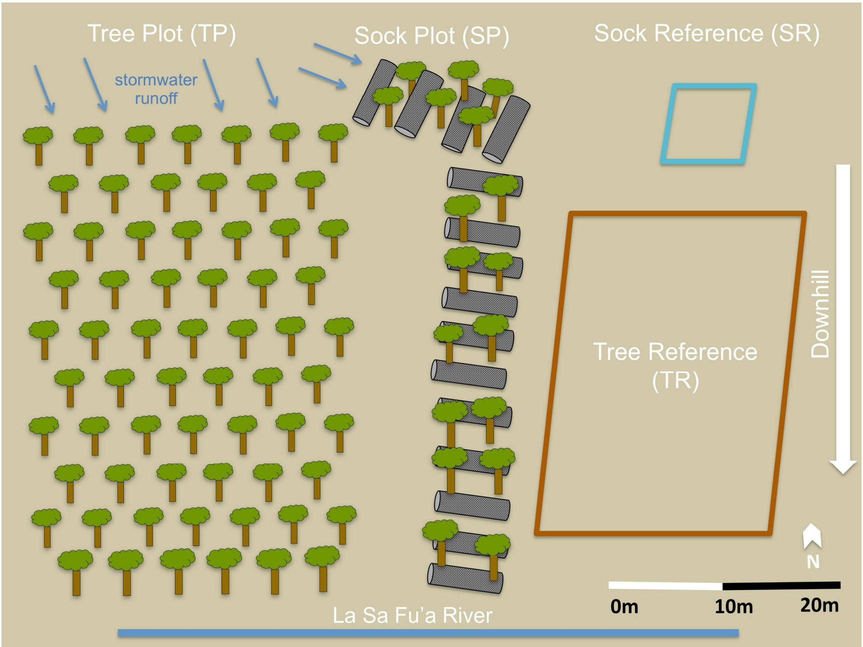

Figure 1 The restoration Plot had an area of 0.4 hectares. It was treated in June 2012. 200 tree seedlings were planted and 54.3 m of sediment filter socks were planted. Soil accumulation and soil health in treatment areas were compared to reference plots to determine effectiveness of watershed management techniques.

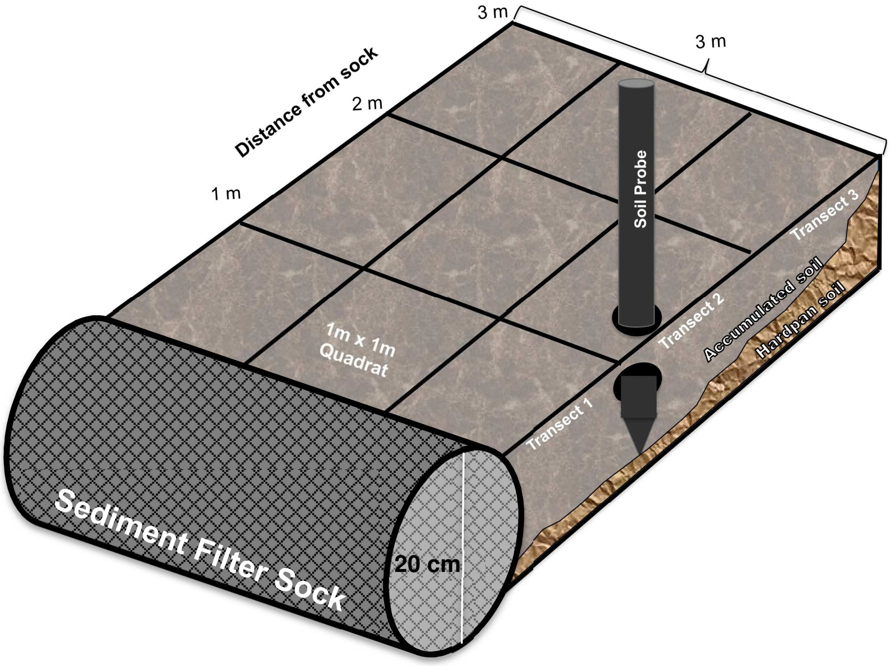

Figure 2 Diagram of method developed to measure soil accumulation in the restoration plot. 1m x 1m quadrats were laid along transects near trees and sediment filter socks. A metal probe was used to measure the depth of soil in three random points per quadrat then averaged.

Table 1 Restoration plot soil depth measurements and total mass of accumulated soil in the Tree Plot.

Mean Tree Plot Soil Depth (cm)	Mean Reference Plot Soil Depth (cm)	Difference in soil depth (cm)	Area of tree plot (m^2)	Volume of Soil Accumulated (m^3)	Mass of Accumulated Soil (kg)
14.4	10.0	4.5	1652	74.34	1.05×10^5

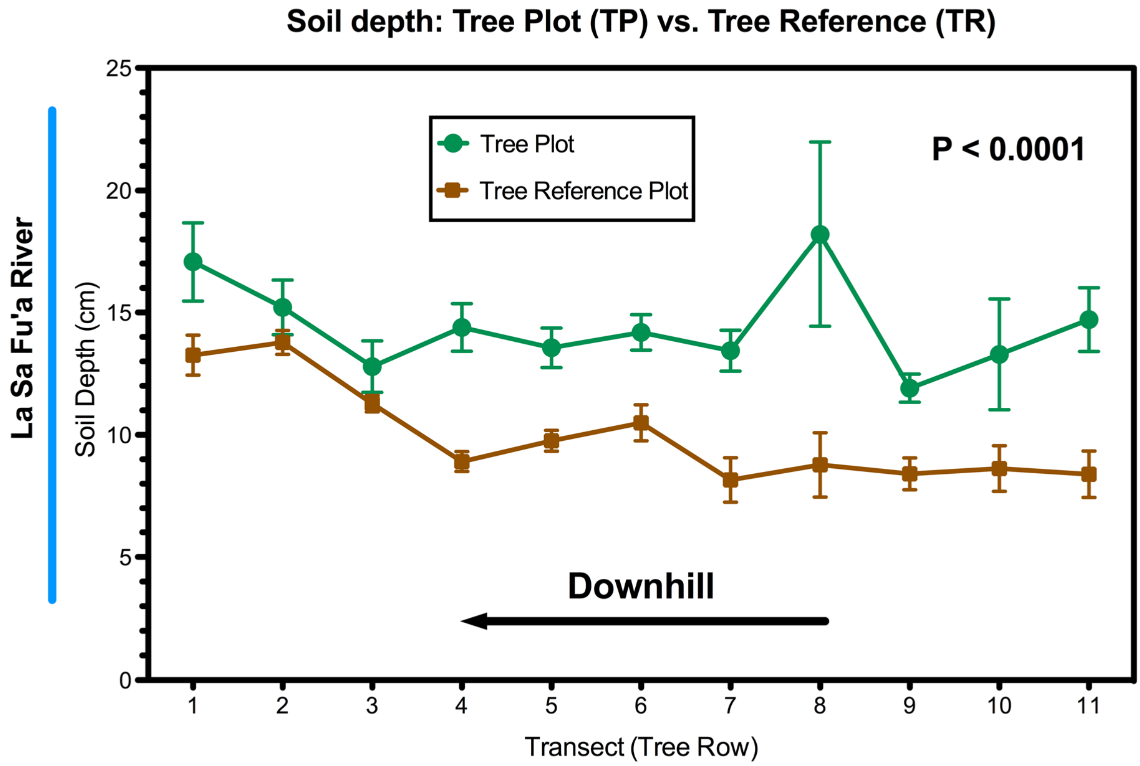

Figure 3. Soil depth of tree planting plot vs. reference plot: Soil accumulation was measured in Restoration Plot 2 using soil probes and compared between the Tree Plot and Reference Plot. The mean soil depth difference between the two areas was 4.46cm. The total mass of accumulated soil in the tree plot was 77.2 metric tons. Error bars indicate standard error of mean (SEM). (P<0.0001, t=6.6, df=20)

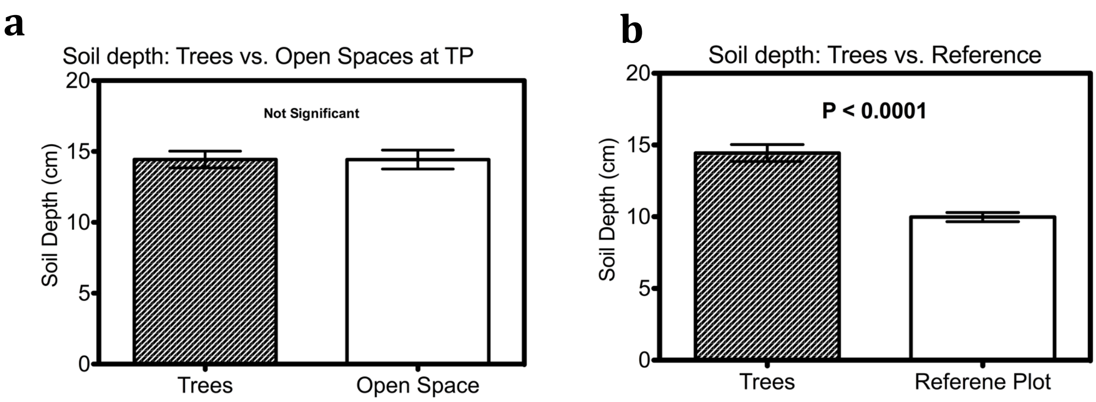

Figure 4 a) Soil depth measurements taken directly behind trees was not significantly different from those taken in open spaces at the TP, indicating trees influence an area greater than the footprint of their canopies. b) Soil depth measurements taken directly behind trees at TP were significantly greater than measurements taken in TR. (P<0.0001, t=6.606, df=83)

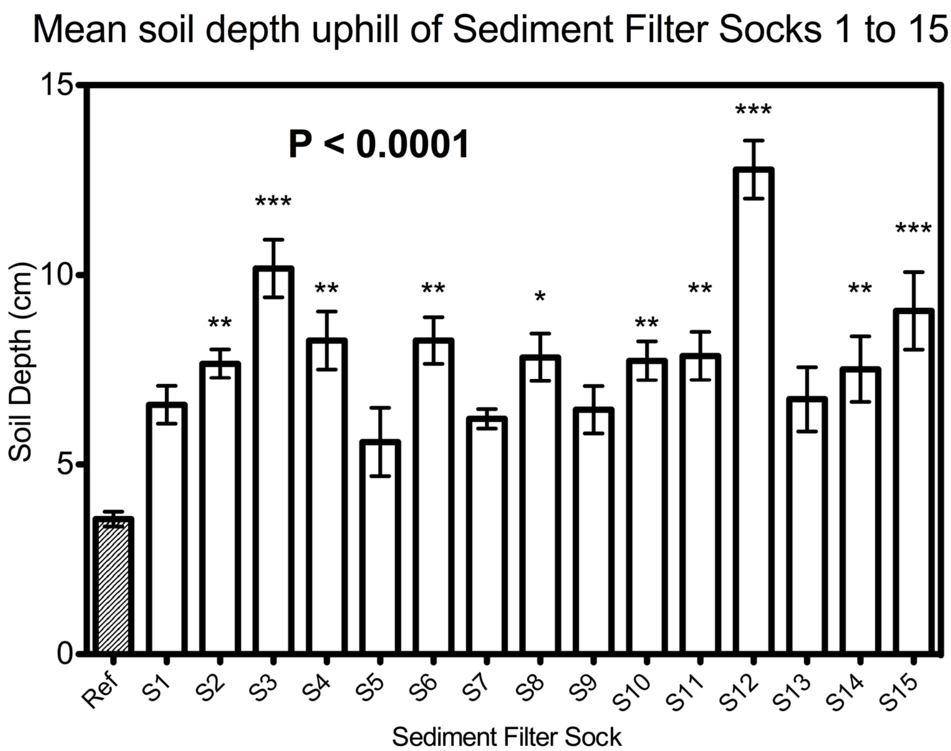

Figure 5 Mean soil depth measurements collected using a soil probe on the uphill side of Sediment Filter Socks 1-15 and at SR. Soil depth was significantly greater behind sediment filter socks than at SR. Error bars indicate standard error of mean (SEM). * indicates statistical significance (P<0.0001, F=16, df=123).

Table 2 Sock Plot (SP) sediment sock lengths, treatment area, and mass of accumulated soil.

Sediment Sock	Sock Length (m)	Area treated (m^2)	Sediment accumulated (kg)
S1	4.4	9	385.9
S2	4.6	9	433.3
S3	5.4	6	561.2
S4	3.4	6	401.4
S5	3	9	261.8
S6	3	6	401.4
S7	3	9	338.9
S8	2.6	4	242.5
S9	4.1	3	123.1
S10	3	9	533.9
S11	3.4	9	550.4
S12	4.2	9	1173.1
S13	3.6	9	404.7
S14	3.7	9	515.6
S15	2.9	9	700.8
TOTAL	**54.3 m**	**115 m^2**	**7027.9 kg**

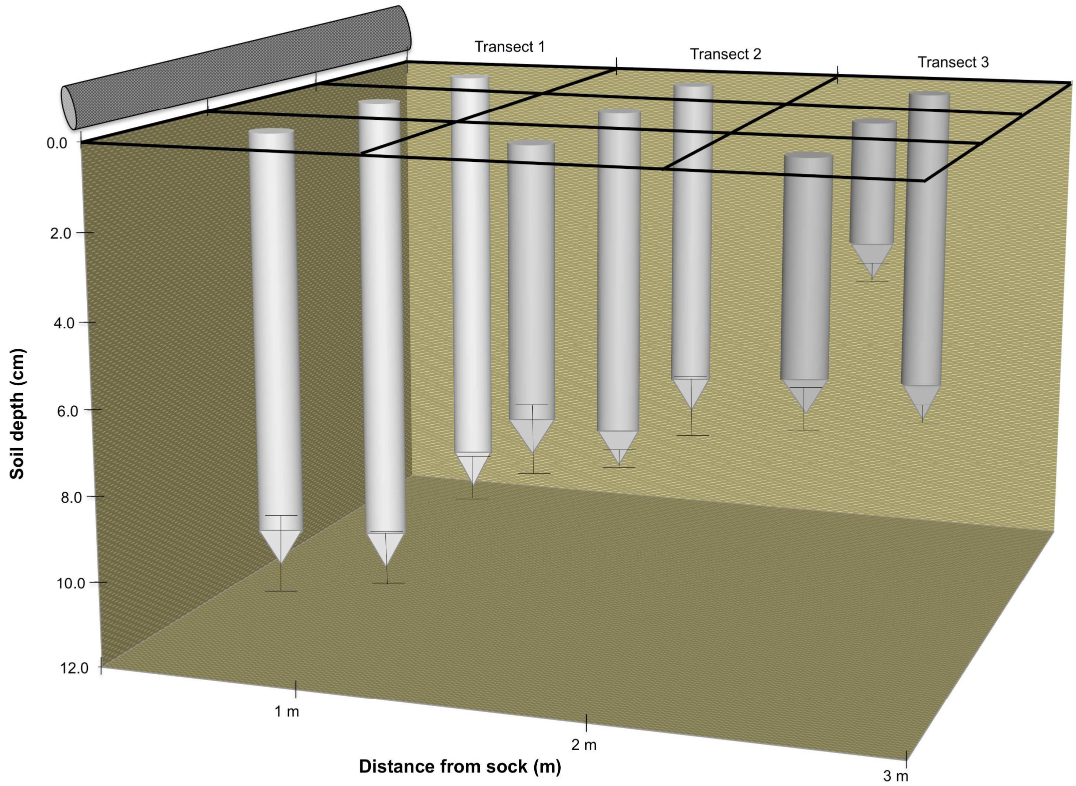

Figure 6. Mean soil depth measurements collected using a soil probe on the uphill side of Sediment Filter Sock 14. Soil depth was greater directly behind the sediment sock and tapered off with increasing distance from the sock. Error bars indicate standard deviation.

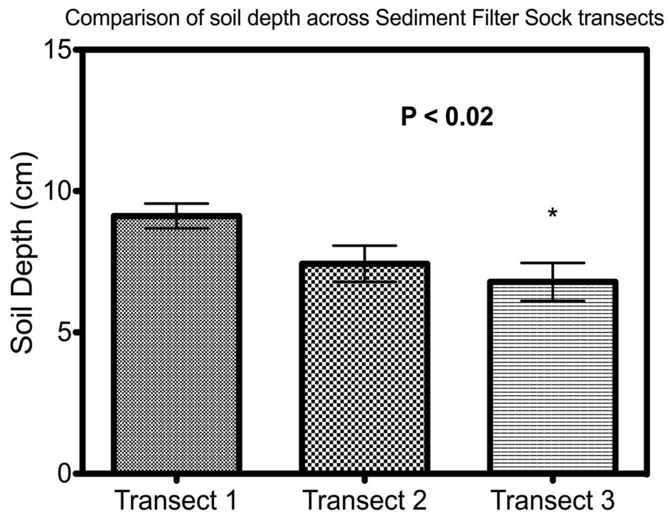

Figure 7 Parallel transects were placed at 1, 2, and 3 m distances behind each sediment filter sock (Figure 1). The mean soil depth of transects across all socks was compared. Soil depth decreased with increasing distance from socks. Error bars indicate standard error of mean (SEM). * indicates statistical significance ($P<0.02$, $F=4.367$, $df=38$)

Table 3 Tree planting and survival data from the restoration plot. Trees seedlings were planted in June 2012. Survival numbers were collected in March 2014 (21 months later). *Artocarpus mariannensis*, *Premna obtusifolia*, and *Calophyllum inophyllum* were the native tree species planted.

	Planted	Survived	Survival rate (%)
Natives	59	8	13.6
Acacia auriculiformes	41	23	69.7
Total	92	31	33.7

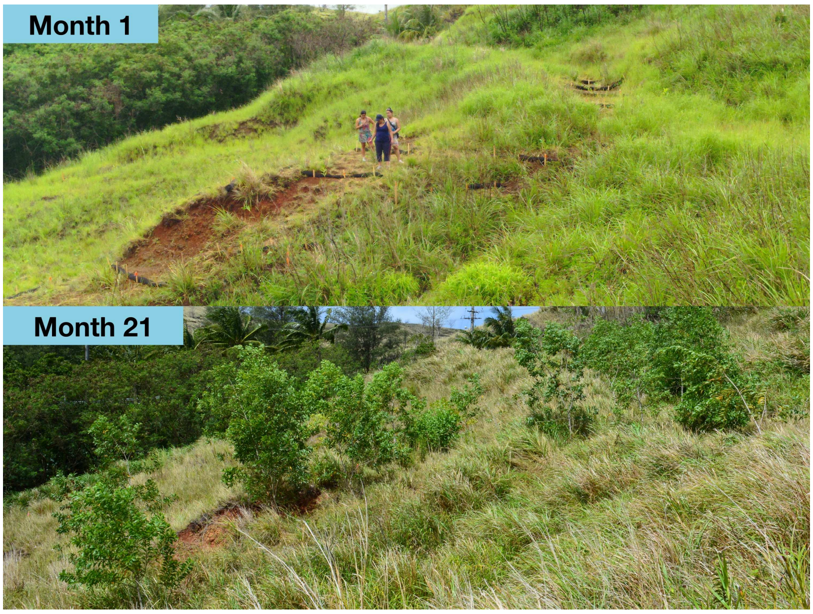

Figure 8 Time series photographs of Restoration Plot 2 Sock Plot (SP). Sediment filter socks were installed and *Acacia auriculiformes* tree seedlings were interspersed between the socks. Trees displayed healthy characteristics and heights of 7 m or greater 21 months after tree seedlings were planted.

Figure 9 Time series photographs of Restoration Plot 2 Sock Plot (SP). An eroding hillside was chosen for treatment. Sediment filter socks were installed and *Acacia auriculiformes* tree seedlings were interspersed between the socks. The area was nearly completely revegetated after 11 months.

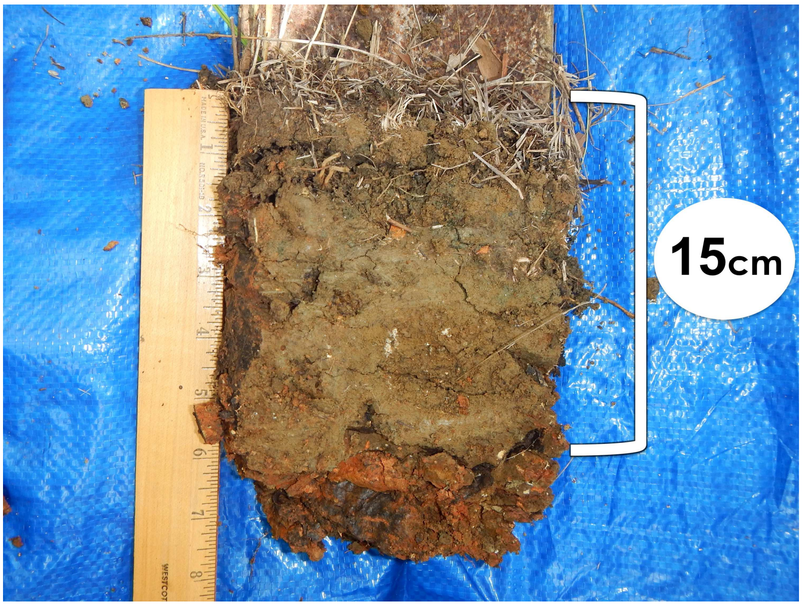

Figure 10. A soil profile removed from the ground used to confirm soil depth measurements taken with a soil probe. The top 15cm in the profile represents accumulated soil and detritus that deposited behind the sock. The soil profile displays a discontinuity at 15 cm depth and a shift to hardpan soil, or the pre-existing soil base.

3 m
3 m
Distance from sock
2 m
1 m
Soil Probe
1m x 1m Quadrat
Transect 1
Transect 2
Transect 3
Accumulated soil
Hardpan soil
Sediment Filter Sock
20 cm
Soil depth probing method to determine trapped sediment
Tree Plot (TP)
Sock Plot (SP)
Sock Reference (SR)
stormwater runoff
Tree Reference (TR)
Downhill
N
0m
10m
20m
La Sa Fu'a River