Traditional datu cactus (*Ritterocereus griseus*) fences reduce run-off rates and transport of sediment and nutrients on hillsides in Bonaire, Dutch Caribbean

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ABSTRACT

Most reef building corals require seawater with low nutrients and sediment loads to thrive. On coral reefs around the world, increases in run-off and its constituent pollutants are damaging and killing reef building corals due to poor coastal zone management practices. In the marine environment, mangroves provide protection for coral reefs by filtering sediments and absorbing nutrients from run-off. On Bonaire, *Ritterocereus griseus*, a common cactus species, has the potential to act as a natural filter, analogous to mangroves in the marine environment, on hillsides where run-off is problematic. This research sought to determine the amounts of run-off, phosphate and sediment transported down-slope of plots with cactus fences and plots without fences. Experimental plots with cactus fence were compared to plots without cacti by utilizing simulated rainfall and catching the run-off to measure the difference in volume, phosphate and sediment loads between plots. This study determined that *R. griseus* reduces the volume of run-off and the amount of sediment and nutrients transported down-slope. The use of cactus fences could increase the resilience on Bonaire's reefs by decreasing sediment and nutrient inputs to near shore waters and are a sustainable resource on the small island.

INTRODUCTION

Sediment run-off (Rogers 1990) and excess nutrients (Hallock and Schlager 1986) are damaging coral reefs in the Caribbean (Rivera-Monroy et al. 2004). The world-renowned coral reefs in Bonaire are declining and are at risk of being destroyed (De Meyer and MacRae 2006). In the past few years, many construction sites have appeared on the hillsides and along the coast of Bonaire (De Meyer and MacRae 2006). Bonaire has not implemented sediment retention practices and heavy rainfall events cause large amounts of sediment to be washed into the ocean (De Meyer and MacRae 2006). In addition, feral ungulates, such as donkeys and goats, graze on the ground cover, leaving soil exposed and increasing erosion on hillsides (De Meyer and MacRae 2006). The fine particles in run-off cloud the water and damage corals in two ways. First, by attenuating light, particles prevent photosynthetic coral symbionts (zooxanthellae) from absorbing light needed for photosynthesis (Rogers 1990). Secondly, too much sediment can push corals beyond their usual cleansing threshold whereby they can no longer rid themselves of sediments, which results in mortality in reef building corals (Tomascik and Sander 1987).

Figure 1. Inlay: Digital image of Bonaire indicating study area (Earth Sciences and Image Analysis Laboratory, NASA Johnson Space Center). Digital Globe image indicating the cactus fence treatment site (12°11'2.70"N, 68°16'40.39"W, labeled A) and the no cactus fence treatment site (12°11'2.83"N, 68°16'43.00"W, labeled B).

While all plants require nutrients to thrive, coral reef ecosystems are adapted to low nutrient levels (Littler et al. 2006). Increased nutrient levels, along with the global problem of decreased herbivory on reefs caused by over-fishing, can increase the standing stock of macroalgae leading to phase shifts from coral to algal dominated reefs (Hughes 1994). Nutrients can also inhibit the formation of calcium carbonate, $CaCO_3$, the molecule corals use to build their skeletons (Hallock and Schlager 1986; Rogers 1990). Studies have shown that high concentrations of phosphate result in decreased rates of calcification (Kinsey and Davies 1979; Snidvongs and Kinzie 1994). High phosphate levels can also have a direct relationship with coral mortality rates because they increase water turbidity, complicating light absorption for zooxanthellae (Walker and Ormond 1982). In addition to direct damage to corals by sediments due to smothering and the effects of nutrients on algal growth that can allow algae to outcompete corals; increases in sediments and nutrients via run-off can stress reef-building corals, making them susceptible to disease (Rabalais 2002)

Vegetation filters are economical, self-sustaining and have proven to be effective in retaining sediments and in absorbing nutrients (Abu-Zreig et al. 2003). Several species of scrubs are successful in preventing run-off by physically blocking sediments and impeding the water's path (Casermeiro et al. 2004). Casermeiro et al. (2004) concluded that areas densely packed with Rosemary shrubs are successful at preventing erosion and run-off. On Bonaire, the practice of building living fences, similar to those of northern Africa and parts of Europe (Le Houérou 1996), using *R. griseus* is utilized to indicate borders and contain livestock.

Figure 2. Photograph of the cactus fence located along a road on a hillside in Antriol, Bonaire, NA (12°11'2.70"N, 68°16'40.39"W).

Moreover, in Tunisia and Algeria cacti are planted in along contours in open areas to reduce run-off and wind-blown erosion of soils and to enable better watershed management by enhancing the quality (nitrogen content) and permeability of soils (Le Houérou 1996). Bonairean cactus fences may provide similar benefits in terms of reducing run-off and erosion of sediments as other vegetation like scrubland and the cactus fences of northern Africa (Le Houérou 1996; Casermeiro et al. 2004) or by removing nutrients as has been suggested for mangroves (Roberston and Phillips 1995).

Figure 3. Photograph of no cactus area located about 0.08 km from the cactus fence along the same road in Antriol, Bonaire, NA (12°11'2.83"N, 68°16'43.00"W).

This study focused on *R. griseus*, an abundant cactus species on Bonaire, commonly known as the datu (De Boer 1996). Island residents often make living fences out of it since it is plentiful, affordable and unattractive to goats and donkeys. *R. griseus* branches are cut and lined up perpendicular to the thin layer of topsoil (De Freitas el al. 2005), where they regenerate shallow roots. Shallow root systems have been known to be effective in quickly storing large amounts of water (Cody 2002) and nutrients in dry climates (Nobel 1989). Presently, cactus fences, which have proven effective at keeping livestock inside or outside of yards and fields, may have other valuable functions such as sediment retention, nutrient removal or reduction of run-off, especially on sloping landscapes. The following hypotheses were tested regarding cactus fences in Bonaire: (H_1) smaller amounts of phosphate (mg L^{-1} s^{-1}) would be transported by run-off on plots with *R. griseus* fences than plots without fences; (H_2) smaller amounts of sediment (g L^{-1} s^{-1}) would be collected down-slope of plots with cactus fences than plots without cactus fences; and (H_3) run-off rates (mL s^{-1}) would be lower on plots with *R. griseus* fences than plots without cactus fence.

The results of this study could be of great interest and consequence for Bonaire. Cactus fences are a widespread natural resource that could be used to retain sediments on hillsides and potentially aid the island in managing run-off during rain events. Run-off carries with it nutrients, herbicides, and pesticides that can harm coral reefs (Larsen and Webb 2009). *R. griseus* fences could increase coral resilience by reducing the harmful effects of run-off.

MATERIALS AND METHODS

Study Site

This study took place on Bonaire, an island that is part of the Dutch Caribbean (Fig. 1). Bonaire is approximately 280 km² (De Meyer and MacRae 2006) and is located 87 km north of Venezuela (De Freitas et al. 2005). The island has both semi-arid and arid regions, with under 80 cm and 50 cm of annual rainfall, respectively (De Freitas et al. 2005). Despite arid conditions, there is a rainy season during which major rainfall events occur (De Freitas et al. 2005). The majority of the island ranges in altitude from 4 m to 15 m above sea level (De Freitas et al. 2005). Although there is not great topographical relief, many houses in Nord Saliña, Republic, and other neighborhoods are built on hillsides where erosion is occurring due to the removal of ground cover by feral ungulates or construction of new homes (De Meyer and MacRae 2006).

This study took place in Republic, a residential neighborhood located north of the capital, Kralendijk (Fig. 1). A 9 m long section of 13-month old cactus fence was identified along a dirt road in Republic (12°11'2.70" N, 68°16'40.39" W, Fig. 2). Approximately 0.08 km away from the cactus fence, along the same dirt road, three nonconsecutive sections of 9 m total without cactus or other vegetation were chosen for the no

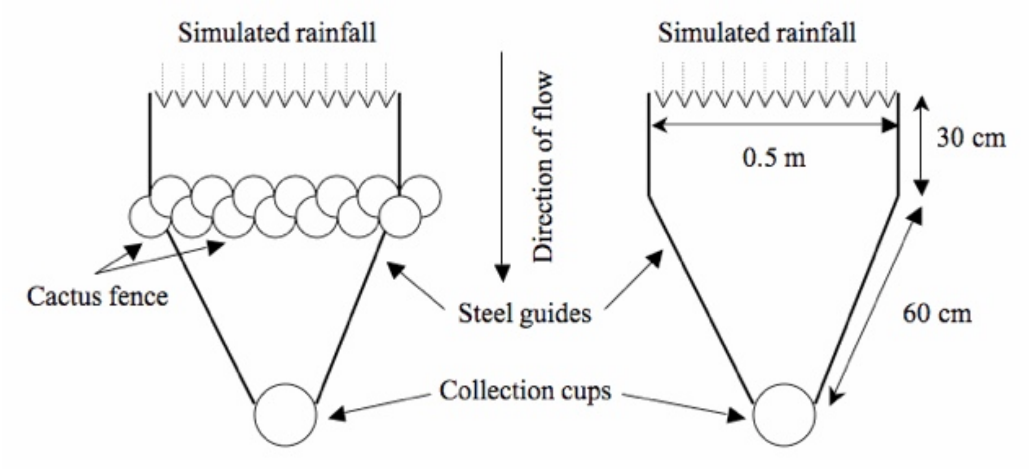

Figure 4. Diagram of cactus treatment plots (left) and no cactus control plots (right) showing the upslope simulated rainfall, direction of run-off, steel guides, scale of plots, cactus fence and collection cups.

cactus treatment plots (12°11'2.83" N, 68°16'43.00" W, Fig. 3). Mean slope for the cactus and no cactus areas were 12.3 ± 1.7° and 12.0 ± 2.3°, respectively. Experimental plots at each location, cactus and no cactus, were chosen at random and each plot was only used once. Treatments were carried out by sequentially alternating between the cactus and no cactus locations to reduce the possible effects of time or day.

Simulated Rainfall Experiments

Prior to experimentation, the slope of each plot was determined using a level. The level was placed in the middle of the plot with the up-slope end located 15 cm before the cactus fence or 30 cm up-slope of the middle of the plot in no cactus treatments. The shape of the experimental set-up was similar to Abu-Zreig et al. (2003). Trials were run in an identical manner for both cactus treatment and no cactus treatment plots. Each plot was approximately 0.5 m wide (Fig. 4). A 0.5 m length of PVC pipe with twenty-four holes (0.3 cm diameter each) spaced equally distance apart, was used to simulate a rainfall event on the plots (Fig. 5). For each trial, 3.79 L of water was poured into the rain simulation apparatus, which was held approximately 10 cm above the ground and 15 cm uphill of the cactus fence. Two pieces of stainless steel, 60.7 cm x 5 cm, were placed along the ground on each side of the plot to guide the water down-slope (Fig. 4). Run-off was directed by two additional stainless steel pieces of the same dimensions that came together in the shape of a 'V' at a collection cup (567 mL). The cup was buried in the ground, up to its rim, at the base of the 'V' to collect run-off water (Fig. 4). A rectangular piece of latex, approximately 14 cm x 22 cm, was placed under the guides at the base of the 'V' to further aid in funneling water into the collection cup. This prevented the soil that had been disturbed while digging a hole for the collection cup from being carried in the run-off. The simulated rainfall lasted 45 s. Run-off was collected in the cup during the same period of time or until the collection cup was full, whichever came first. If the cup filled before the end of the simulated rainfall, the time to fill the cup was recorded. The same method was used for the no cactus fence treatment, except in order to compensate for the distance that would have been taken up by cactus in the experimental plot, water was poured 30 cm before intersection of the parallel and 'V' shaped guides in the no cactus plot (Fig. 4). Ten replicates were completed for the cactus fence treatment and nine replicates were completed for the no cactus fence treatment because the steel guides failed in the tenth replicate for the no cactus treatment plots.

Figure 5. Rainfall simulation apparatus; 0.5 m length of PVC pipe with an opening on the top for the addition of water and 24 holes on the bottom (0.3 cm diameter each) spaced approximately 1 cm apart to dispense water on to experimental plots.

Phosphate transport rate

Prior to each trial, 12 g of Scott's Miracle-Gro® was added to the water, as instructed by the manufacturer. Miracle-Gro® Water Soluble All Purpose Plant Food contains 8 % phosphate. The amount of phosphate dissolved in the water was tested using the Red Sea Phosphate Marine and Freshwater Test Lab kit to ensure that each sample contained the same amount of phosphate. Mean level of phosphate before each trial was 0.5 mg L^{-1}. After each trial, the amount of phosphate in the collection cup was calculated in mg L^{-1} s^{-1}. Mean phosphate transport rates (± SD) were calculated for cactus treatment and no cactus plots.

Sediment transport rate

Water samples were held for 1 h at 4 °C to allow the sediment particles to settle. Water was decanted into a beaker and the volume was recorded. To determine sediment weight, sediments were placed in pre-weighed aluminum foil boats and dried in an oven at 40 °C for 24 h. After drying, the amount of sediment collected was calculated in g L^{-1} s^{-1}, by subtracting the initial weight from the final weight then accounting for the volume (L) and time (s). Mean sediment transport rates (± SD) were calculated for cactus treatment and no cactus plots.

Run-off rate

The run-off rate was calculated by dividing the run-off volume by the trial time (mL s^{-1}). Mean run-off rates (± SD) were calculated for cactus and no cactus treatment plots.

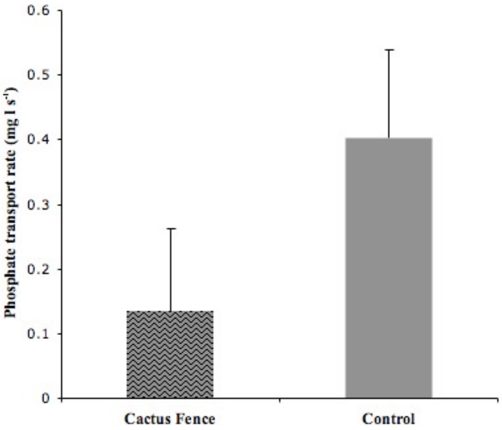

Figure 6. Comparison of mean phosphate transport rate ± SD (mg l^{-1} s^{-1}) collected from run-off on cactus fence (n = 10) and no cactus fence treatments (n = 9).

Statistical Analysis

One –tailed t-tests were used to determine if there were significant differences in amounts of sediments and phosphate transported across treatment plots (☐ = 0.05) and a one-tailed t-test was used to determine if run-off rates were significantly different between plots with cactus and without cacti (☐ = 0.05).

Results

Phosphate transport rate

The rate of transport of phosphate down-slope of the no cactus treatment was 3 X that of the cactus treatment plots (Fig. 6). The mean transport rate of cactus treatment plots was 0.13 ± 0.13 mg L^{-1} s^{-1} whereas, the mean transport rate on no cactus plots was 0.40 ± 0.14 mg L^{-1} s^{-1} (Fig. 6). Mean phosphate transport rate was found to be significantly lower over cactus treatment plots than no cactus treatment plots ($p < 0.001$).

Of the 2 mg of phosphate that was contained in the simulated rainfall, 80.6 % was delivered to the collection cup in the no cactus treatments versus 26.7 % of the phosphate for the cactus treatment.

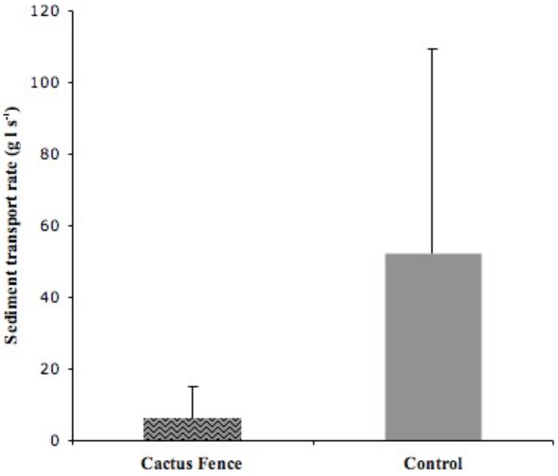

Figure 7. Comparison of mean sediment transport rate ± SD (g l^{-1} s^{-1}) collected from run-off on cactus fence (n = 10) and no cactus fence treatments (n = 9).

Sediment transport rate

The mean sediment transport rate was significantly lower over cactus treatment plots than no cactus treatment plots (p = 0.012). The rate of sediment transport in no cactus treatment plots was 8 X higher (52.1 ± 57.4 g L^{-1} s^{-1}) than cactus treatment plots (6.3 ± 8.8 g L^{-1} s^{-1}; Fig. 7).

Run-off rate

The mean run-off rate across no cactus fence plots was 3 X that of the cactus treatment plots (Fig. 8). The mean run-off across cactus fence treatments was 3.9 ± 19.9 mL s^{-1} whereas; the mean run-off on no cactus treatment plots was 12.4 ± 18.6 mL s^{-1}. In 45 s, 2.1 % of the water added to cactus treatments was collected, whereas 6.6 % of the water was collected from no cactus treatments. The t-test indicated a highly significant difference between run-off rates from cactus treatments versus no cactus treatments (p < 0.001).

DISCUSSION AND CONCLUSIONS

It is vital to reduce the amounts of phosphate and sediments reaching the ocean via run-off in order to sustain coral reef ecosystems. The results of this experimental study show that traditional cactus fences can be utilized to reduce the amount of run-off reaching coral reefs in Bonaire. By utilizing simulated rainfall, the amount of water added to plots was standardized and may or may not be representative of actual rainfall events in Bonaire. Prior to implementing programs aimed to increase use of cactus fences to aid in watershed management in Bonaire, a better understanding of the range and intensity of rainfall events and how the ability of fences to decrease flow of run-off over longer periods of time are necessary.

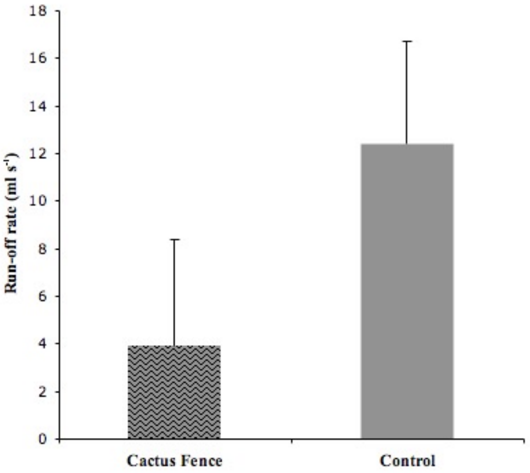

Figure 8. Comparison of mean run-off rate ± SD (ml s^{-1}) from 0.5 m cactus fence (n = 10) and no cactus fence treatments (n = 9).

Phosphate transport rate

Phosphate can negatively influence coral reefs because it can inhibit the calcification processes of corals and promote algal growth (Kinsey and Davies 1979; Hallock and Schlager 1986; Rogers 1990). The results of this study support the hypothesis that significantly lower levels of phosphate would be transported across experimental plots with cactus fence than no cactus fence plots. This experiment did not measure phosphate absorption but rather the mechanical withholding of phosphate in the presence or absence of cactus fence. By allowing less water to flow through the fence, *R. griseus* prevented phosphate from passing through as well. Cactus fence plots retained 73 % of the phosphate applied as a component of simulated rainfall, whereas plots without cactus retained only 19 % of the phosphate. Therefore, *R. griseus* fences are capable of reducing the amount of phosphate transported to the ocean.

The use of vegetation as a method for decreasing water flow and thereby increasing nutrient uptake has been documented in other studies (Gopal 1999; Abu-Zreig et al. 2003). Abu-Zreig et al. (2003) concluded that filter length and plant density are important factors in increasing filter efficacy for phosphorus. The effect of cactus density was not investigated in this study but could affect the overall absorption rates. Another factor, not addressed in this study is the capability of nutrient absorption by the shallow root system of *R. griseus,* a root system type known to readily absorb nutrients (Nobel 1989). Future studies of uptake rates of *R. griseus* are necessary to determine if the cacti or the soils around cacti can absorb nutrients as well as decrease run-off. As discussed in Le Houérou (1996), cactus fences (*Opuntia* spp.) can increase the nitrogen levels and permeability of soil along fence rows substantially when compared to adjacent open fields.

Sediment transport rate

Sediments harm corals because they increase the turbidity of the water (Walker and Ormond 1982; Rogers 1990). Corals are not only suffocated, but cannot attain sunlight for their algal symbionts (Rogers 1990). The results of this study support the hypothesis that less sediment would be transported down-slope in plots with cactus fence when compared with areas without cactus (p = 0.012). The weight of sediments transported across no fence treatments was 8-fold higher than the cactus fence plots (Fig. 6). The cactus fence demonstrated effectiveness at retaining sediments in comparison to non-vegetated areas. Decreasing sedimentation is an essential element in maintaining normal recovery intervals for coral reefs (Paine et al. 1998).

Studies have already shown the plant density is a useful tool in decreasing sedimentation (Abu-Zreig et al. 2003; Casermeiro et al. 2004). Casermeiro et al. (2004) concluded that increased plant cover decreases erosion in studies with different types of scrubs, rather than cacti that were used in the current study. However, the same effect should apply because while the plants differ in morphology and height, they both have shallow root systems. Pearce et al. (1998) showed that plant height has no effect on sediment retention.

Run-off rate

As predicted, run-off rates were lower for areas with cactus fence compared to the no cactus fence plots. The difference in mean run-off rate from cactus plots and no cactus fence plots was highly significant, reducing run-off from the plot by 3 X. The results of this study suggest that *R. griseus* may be a useful resource in protecting Bonaire's coral reefs. Decreasing the amount of run-off entering the ocean is crucial as run-off often carries nutrients, herbicides, pesticides and sediments (Larsen and Webb 2009), which are all harmful to coral reefs (Walker and Ormond 1982; Rogers 1990). An indirect relationship between plant density and run-off rate has already been shown for woodland areas (Greene et al. 1994). Greene et al. (1994) concluded that this is because plant bases can create areas for water to quickly seep into the soil.

Estimated over a 10 m area, a cactus fence would allow 78.2 mL s^{-1} run-off whereas, a 10 m no cactus area would allow 248.6 mL s^{-1}. This evidence suggests that *R. griseus* can slow run-off rate and could be applied on a larger scale on hillsides in Bonaire. *R. griseus* fences are capable of holding back large amounts of run-off and therefore phosphate and sediments. Cactus fences may be a useful tool in reducing the anthropogenic influences occurring on coral reefs of Bonaire. The cactus is abundant around the island and requires little in terms of upkeep when used as a fence. Use of the cactus as fencing appears to be a sustainable practice because sections are removed from existing plants that continue to grow and the section in the fence will root and also thrive. Erosion is evident on the hillsides of Nord Saliña and Republic and run-off is entering the nearshore environment from construction sites located on the waterfront, which are typically cleared of all vegetation prior to construction. The use of cactus fences in the neighborhoods located on hillsides would likely be effective in reducing run-off to the ocean, especially if the fences were constructed on lots prior to building new houses. It may be less plausible to use cactus fences on the waterfront for large construction sites because fences would need to be constructed in advance of the project to give the cacti time to root.

The use of cactus fences is an example of how local practices, derived from tradition, as opposed to science, provide insight to ecological processes and sustainable solutions for local problems. For decades, Robert Johannes has compared the practical knowledge of artisanal fishermen to scientific knowledge accepted by research communities. In 2000, he determined that the fishermen of Marovo Lagoon, Solomon Islands, possessed information pertaining to local fish behavior that was untested by the scientific world until 2000 (Johannes and Hviding 2000). By observing sea birds gathering above the water, fishermen could tell which predatory fish were below the surface (Johannes and Hviding 2000). Traditional, non-science based knowledge has been passed down from generation to generation in the Dutch Caribbean. In Curaçao, people who could not afford wells formerly used the Kadushi cactus, *Subpilocereus repandus*, as a water purifier (Morton 1967). They placed pieces of despined cactus in muddy water and when they returned days later the water was reported to be potable (Morton 1967). These traditional practices capitalize upon ecologically important occurrences that have only recently been recognized by scientific communities. *R. griseus* fences are among these beneficial customs as they reduce nutrient transport rates, sediment transport rates and run-off rates.

ACKNOWLEDGMENTS

I would like to thank my mentor Dr. Rita Peachey for her invaluable advising and countless hours of field work. Thank you to Jill Lau, Lauren Saulino, Kate Jirik and Amanda Hollebone for their revisions and insight, Evelyn Anthony for use of her cactus fence, and CIEE for providing the opportunity and resources for this study. Additional thanks to Dr. Diane Felsen and Dr. Catherine McCormick for their greatly appreciated edits.

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