Estuarine, Coastal and Shelf Science xxx (2016) 1–8

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

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

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ARTICLE INFO

Article history:
Received 28 February 2016
Received in revised form
18 June 2016
Accepted 27 June 2016
Available online xxx

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 2121 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.

1. 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 and Smith, 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 et al., 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 et al., 1982). Areas of volcanic soils exposed through erosion are referred to as badlands (Kottermair et al., 2011).

On small islands, land-based pollutants need only travel short

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http://dx.doi.org/10.1016/j.ecss.2016.06.027

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).

1.1. 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 h, 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 1000 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., 2002; Wolanski et al., 2003, 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.

1.2. 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).

2. Materials and methods

2.1. 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*.

2.2. 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.

2.3. 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

Please cite this article in press as: Shelton, III, A.J., Richmond, R.H., Watershed restoration as a tool for improving coral reef resilience against climate change and other human impacts, Estuarine, Coastal and Shelf Science (2016), http://dx.doi.org/10.1016/j.ecss.2016.06.027