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Terrestrial degradation impacts on coral reef health: Evidence from the Caribbean

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ABSTRACT

Coral reefs are in decline worldwide. While coral reef managers are limited in their ability to tackle global challenges, such as ocean warming, managing local threats can increase the resilience of coral reefs to these global threats. One such local threat is high sediment inputs to coastal waters due to terrestrial over-grazing. Increases in terrestrial sediment input into coral reefs are associated with increased coral mortality, reduced growth rates, and changes in species composition, as well as alterations to fish communities. We used general linear models to investigate the link between vegetation ground cover and tree biomass index, within a dry-forest ecosystem, to coral cover, fish communities and visibility in the case study site of Bonaire, Caribbean Netherlands. We found a positive relationship between ground cover and coral cover below 10 m depth, and a negative relationship between tree biomass index and coral cover below 10 m. Greater ground cover is associated to sediment anchored through root systems, and higher surface complexity, slowing water flow, which would otherwise transport sediment. The negative relationship between tree biomass index and coral cover is unexpected, and may be a result of the deep roots associated with dry-forest trees, due to limited availability of water, which therefore do not anchor surface sediment, or contribute to surface complexity. Our analysis provides evidence that coral reef managers could improve reef health through engaging in terrestrial ecosystem protection, for example by taking steps to reduce grazing pressures, or in restoring degraded forest ecosystems.

1. Introduction

Coral reefs are declining worldwide, due to a range of global, regional and local drivers (Kennedy et al., 2013; Wilkinson, 1999). Globally, climate change-induced ocean warming is recognised as the most significant threat, and coral bleaching arising from ocean acidification threatens corals worldwide (Hughes et al., 2003). Regional threats, such as invasive species (Albins and Hixon, 2008), and local threats such as trawling, over fishing (McClanahan, 1995) or terrestrial sediment run-off (Álvarez-Romero et al., 2011; Fabricius, 2005; Klein et al., 2014; Risk, 2014; Rogers, 1990) also cause significant damage.

Changes in terrestrial ecosystems can impact coral reefs through sediment and nutrient run-off. Run-off extent is determined by multiple watershed factors, including: soil type (Millward and Mersey, 1999; Renard et al., 2000); slope (Boer and Puigdefábregas, 2005; Millward and Mersey, 1999; Renard et al., 2000); urban development (Hunter and Evans, 1995); river and stream presence and length; land use (Hunter and Evans, 1995); and vegetation (Álvarez-Romero et al., 2011; Mateos-Molina et al., 2015; Risk, 2014; Rodgers et al., 2012). Vegetation impacts on sediment run-off varies by vegetation types, particularly ground cover and tree density. Vegetation ground cover anchors surface sediments, and slows water flow, therefore decreasing the amount of sediment dislodged by surface water (Bartley et al., 2014). Tree roots increase surface complexity through surface roots, which again slow water flow while also creating pools of water. The creation of pools is associated with increased water seeping into the soil, and therefore reduced sediment run-off (Bartley et al., 2014). Land use which changes vegetation cover and tree density or size, or alters soil surface structure such as through ploughing or laying of concrete, can therefore impact sediment run-off (Álvarez-Romero et al., 2011; Mateos-Molina et al., 2015; Risk, 2014; Rodgers et al., 2012). The impacts of sediment run-off on the marine

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system can also be altered by waves and currents, with sediments remaining in suspension for longer in higher energy environments, while currents may remove sediment from the coastal area (Rodgers et al., 2012).

Increases in sediment run-off has negative impacts on coral reef ecosystems. Variation between species, and interactions with other reef threats, means that the threshold for damage by sediment is highly context specific (Fabricius, 2005), though some coral species show negative impacts at levels of 3 mg/l of suspended particulate matter (Anthony and Fabricius, 2000). High sediment run-off can impact corals through both increasing suspended sediment, and through sedimentation. Suspended sediment increases water turbidity, reducing light availability. In reduced light coral growth rates are slowed (Fabricius, 2005; Pollock et al., 2014; Stender et al., 2014), coral morphology changes, and structural stability is compromised (Erftemeijer et al., 2012; Fabricius, 2005). High turbidity, often associated with increases in nutrient levels, leads to increases in macroalgae growth, which smother hard corals (De'Ath and Fabricius, 2010). Species richness is reduced, because those species most susceptible to low light levels, and competition with macroalgae, undergo disproportionate damage, leaving only tolerant species (De'Ath and Fabricius, 2010; Fabricius, 2005). Smothering of corals through sedimentation directly leads to coral mortality, due to restricting light penetration needed for photosynthesis (Erftemeijer et al., 2012; Weber et al., 2006). Smothering inhibits feeding polyps, reducing energy intake in heterotrophic corals (Erftemeijer et al., 2012), though these may see improvements for moderate increases in suspended sediment (De'Ath and Fabricius, 2010). Coral morphology changes to favour vertical or sloped, rather than horizontal, surfaces (Erftemeijer et al., 2012), morphology changes which also reduce area suited to light absorption, and can therefore increase the detrimental impacts of low light caused by suspended sediment. Coral recruitment decreases, as juvenile corals struggle to become established on high sediment substrates (Edmunds and Gray, 2014; Jones et al., 2015; Rogers, 1990). Mucus production is increased to provide protection from settling sediments, but also increases coral stress (Erftemeijer et al., 2012). Increased mucus production leads to heightened microbial activity on coral tissue surface, which contributes to anoxic conditions, damaging coral tissues (Weber et al., 2012, 2006). Furthermore, reefs under high sediment loads have unpredictable recovery (Rogers, 1990), and reduced ability to cope with future ocean warming (Maina et al., 2013; Risk, 2014), or algae invasion (Birrell et al., 2005).

Fish populations are also negatively impacted by both suspended sediments and sedimentation. Suspended sediments are related to more random habitat choices of fish larva, reducing survival and, due to preferences for remaining in clear waters, larva dispersal is restricted (Wenger et al., 2011). Predator-prey interactions are modified, with suspended sediments impacting visual recognition of prey, and interfering with chemical signals (Wenger et al., 2013). Fish increase mucus production in their gills in high sediment waters, reducing efficiency of oxygen uptake (Hess et al., 2015). Reduced oxygen uptake slows development of fish larva (Hess et al., 2015; Wenger et al., 2014), and restricts larval dispersal due to reduced energy availability (Hess et al., 2015). Sedimentation can have direct impacts on fish communities, with herbivorous fish negatively associated to high sedimentation (Goatley and Bellwood, 2012).

Within the last 15 years an increasing number of studies have emerged highlighting the importance of conserving watersheds for coral reef conservation (Álvarez-Romero et al., 2011; Beger et al., 2010; Carroll et al., 2012; Cox et al., 2006; Klein et al., 2010; Makino et al., 2013; Tallis et al., 2008), and a number of models have been developed to identify erosion threats (Álvarez-Romero et al., 2014), or to integrate threat management between ecosystems (Cox et al., 2006; Klein et al., 2014, 2012, 2010; Tallis et al., 2008). Empirical studies have predominantly focused on the effects of losses in watershed vegetation directly on sediment run-off. For example, reductions in vegetation cover in a watershed increase erosion risk (Bartley et al., 2014, 2010; Maina et al., 2013; Mateos-Molina et al., 2015), and watershed development, such as increases in agriculture (Bartley et al., 2014; Begin et al., 2014; Carroll et al., 2012); land cleared for construction (Nemeth and Nowlis, 2001); and unpaved roads (Begin et al., 2014) correlate with increases in sediment run-off. But the direct link between watershed-wide ecosystem health and coral reef health (combined coral cover and species richness; abundance, diversity and biomass of fish) has been less widely studied. Relationships between watershed vegetation cover and reef health have been found in coral reefs in Hawaii, though this impact was dominated by the influence of reef characteristics (wave action; depth; and degree of shelter; Rodgers et al., 2012). Improvements in terrestrial conservation in Fiji were estimated to result in a 10% improvement in reef health (Klein et al., 2014), and increases in bleaching have been observed following increases in sediment caused by land clearing for construction (Nemeth and Nowlis, 2001). Palaeontological techniques have been used to estimate historical coral reef cover and species in Caribbean Panama (Cramer et al., 2012) and the Great Barrier Reef (Roff et al., 2012). Sediment cores in the Great Barrier Reef showed increases in sedimentation and nutrient levels following European settlement (Roff et al., 2012), and death assemblages of corals in both locations showed a decline in coral cover correlated to recorded land clearances (Cramer et al., 2012; Roff et al., 2012). Though the nature of these studies precludes testing of causation, as these declines were observed prior to ocean warming, acidification, or bleaching and disease events they suggests that land clearance may have led to coral decline as early as the 19th Century (Cramer et al., 2012; Roff et al., 2012).

In this paper we investigate the link between watershed vegetation and coral reef health, using the coral reefs on the west coast of Bonaire, Caribbean Netherlands, as a case study. Building on previous studies, links between vegetation biomass and ground cover; and reef health are estimated, in terms of impacts on visibility (turbidity), coral and fish. The paper thus provides insights for watershed restoration programs, and adds to the limited empirical data linking the terrestrial ecosystem to reef health.

2. Methods

2.1. Case study site

Bonaire, Caribbean Netherlands, is a special municipality of the Kingdom of the Netherlands, situated in the Southern Caribbean (12° 10′ N 68° 17′ W, Fig. 1), with an area of 294 km^2. Bonaire's terrestrial ecosystem is made up of tropical dry-forest, which receives an average of 500 mm of rainfall per year. Rainfall is highest between October and March, and falls predominantly in short, heavy showers. Bonaire has no above ground rivers or streams, and only a single freshwater spring. The island is well known for its healthy coral reef (Steneck et al., 2015), but has a long history of terrestrial degradation, with invasive herbivores introduced in the 16th Century, and widespread tree felling in the early 1900s (Freitas et al., 2005; Westermann and Zonneveld, 1956). Such changes are recognised as threatening Bonaire's marine ecosystems, due to increases in sediment and nutrient run-off associated with reduced root systems in the terrestrial environment (Slijkerman et al., 2011; Wosten, 2013).

As a fringing coral reef, the majority of Bonaire's corals are found within between 50 m and 100 m offshore, though in some locations