The influence of terrestrial erosion on *Acropora palmata* occurrence on Saba, Dutch Caribbean

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Photo frontpage from an *Acropora palmata* colony at Green Island, Saba (photo by A.E. Mulder).

Abstract

A high influx of sediment resulting from terrestrial erosion, imposes a major threat on coral reef ecosystems worldwide by inducing sedimentation and turbidity. Terrestrial erosion may result from both natural processes and anthropogenic activities. Healthy reefs are important for biodiversity, fisheries, stimulate tourism and provide protection for shorelines. This research examines to what extent terrestrial erosion processes influence the site conditions for elkhorn (*Acropora palmata),* a major reef building and critically endangered coral species, on Saba in the Dutch Caribbean. This research aims to understand the interaction between terrestrial erosion processes and marine ecosystem vitality and to highlight the relevance of inclusion of both marine and terrestrial processes in conservation and management of vulnerable marine ecosystems. By integrating the slope, soil type, land use and vegetation cover, a potential erosion intensity map was created in ArcMap 10.4.1 which shows the predicted severity of erosion on Saba. With the use of this map 16 sampling sites were selected where the presence of *Acropora palmata* was examined and several biotic and abiotic parameters*,* such as presence of wave action, temperature and the size of colonies were measured. The collected data was analysed in R studio with the use of Generalised Linear Models (GLM), Linear Models (LM) and ANOVA. It is found that when the severity of terrestrial erosion increases, the probability of elkhorn occurrence on Saba decreases. Furthermore, it is likely that erosion products entering the reefs result in colony and tissue death. In addition, an interaction was detected which indicated that the more erosion products enter the coral reef ecosystem, the larger the advantage for a colony to be elevated from its surroundings. No effect of terrestrial erosion was detected on the abundance of the species, the colony cross sections and the angle of the most dominant slope the colony had with its substrate. The workflow developed in this research can be applied by research institutes or local governments to assess the effect of terrestrial erosion on coral species in other tropical regions.

Keywords: Terrestrial erosion, Saba, Sedimentation, Turbidity, *Acropora palmata,* Elkhorn, Caribbean coral reefs

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1. Introduction

Severe terrestrial erosion in coastal areas are worldwide resulting in high influxes of sediments in coral reef ecosystems. The erosion can be induced by natural factors such as waves, storms and river flows, but also by anthropogenic influences such as deforestation, specific farming techniques and coastal development (Silva, Leão, Kiuchi, Costa & Souza, 2013 & Bio et al., 2015). The resulting flow of sediments increase the turbidity of the water, limiting the light availability necessary for photosynthesis of the zooxanthellae. These are algae that have a symbiotic relationship with coral polyps and provide them with more than 95 percent of the metabolic requirements (Hoegh-Guldberg et al., 2007). Research by Rogers (1990) states that excessive sedimentation is associated with fewer coral species present and less alive coral. Other negative impacts include abrasion, settlement inhibition, restriction of growth, and reduced calcification resulting in slower rates of accretion of reefs (Rogers, 1990 & Hubbard, 1997 & Segal & Castro, 2011).

Healthy reefs are important for fisheries, stimulate tourism and protect shorelines from wave action, preventing erosion, destruction of property and loss of life (Jameson, McManus & Spalding, 1995 & Johns, Leeworthy, Bell & Bonn, 2001). Coral reefs provide shelter and food for many different organisms and globally five hundred million people live within 100 kilometres of a coral reef while profiting from its services (NOAA, 2008). In this research the relationship between terrestrial erosion at the coast and site conditions of *Acropora palmata* on Saba in the Dutch Caribbean is assessed. *Acropora palmata,* common name elkhorn, is a coral that is classified as critically endangered by The IUCN Red List of Threatened Species. It is a stony coral and a major reef building species that is found in tropical shallow reefs, mostly at upper to mid-reef slopes and lagoons, at depths of 1 to 5 meters or more (figure 1) (Adey & Burke, 1976, Adey, 1978, Croquer, Cavada-Blanco, Zubillage, Agudo-Adriani & Sweet, 2016 & IUCN, 2017). It is a rapidly growing coral but has a low sediment rejection-efficiency (Bak, 1976, Bak & Elgershuizen, 1976 & Bak & Engel, 1979). Since the Pleistocene, elkhorn used to occur all around the Caribbean, typically in the shallow reef crest zone. However, four decades ago in the late 1970s, mass outbreaks of white band disease have drastically reduced the abundance of this species (Aronson & Precht, 2001 & Mumby et al., 2014). Elkhorn is a major reef-building species as it provides three dimensional structures critical to many reef ecosystems, ensuring habitat and shelter to countless marine species (Pandolfi & Jackson, 2006). Therefore it is crucial that elkhorn is protected.

Figure 1: ***Acropora palmata*** **(elkhorn coral) (Source: Olie, 2017).**

For this research, the impact of a growing threat for coral reefs will be studied; the influences of sediment influx through terrestrial erosion (Bryant, Burke, McManus & Spalding, 1998 & Spalding, Ravilious & Green, 2001). This research is executed on Saba, a small, isolated and highly erosive volcanic island, which can be used as a study model for assessing the consequences of erosion processes occurring on coral reefs worldwide (Warren et al., 2015).

This study aims to assess whether coastal erosion and its severity affects elkhorn occurrence on Saba. Furthermore, it is aimed to gain insight in processes concerning the interconnectivity between terrestrial and marine geo-ecosystems and to emphasize the importance of including both marine and terrestrial processes in conservation and management of coral reefs. Lastly it intends to provide a simple workflow to assess the relation between coastal erosion and coral species presence, that can be applied for other tropical islands and tropical areas. In this research the main research question is: to what extent do terrestrial erosion processes influence the site conditions of *Acropora palmata* on Saba? In order to answer this question it is necessary to use a geo-ecological approach that focusses on both the terrestrial processes as the marine processes involved. To reach this goal, sub-questions are specified. Firstly, how do terrestrial erosion processes influence coral growth? A literature review is carried out to gain insight in terrestrial erosion and in the processes that take place when eroded materials enter a fragile coral reef ecosystem. Next, it is assessed how the severity of terrestrial erosion is distributed among the coast of Saba. This encompasses a predictive phase in which a potential erosion intensity map is created and an empirical phase, in which on-site assessment is done to validate the results from the predictive phase. Lastly it is examined if the severity of the terrestrial erosion at the coast affects the presence of elkhorn colonies on Saba. Fieldwork is conducted underwater on areas connected to different levels of erosion intensity to assess the on-site habitat conditions and to check if elkhorn is present. Characteristics of elkhorn colonies are also examined.

Based on the common perception that influx of sediment has a negative impact on the settlement, growth and survival of coral species (Roger, 1990, Segal & Castro, 2011, Silva et al., 2013 & Oleson et al., 2017), it is hypothesised that as the severity of the erosion on the coast of Saba increases, the probability of elkhorn occurrence decreases. In addition, it is expected that colonies in a low erosion region are in better condition than colonies in regions affected by severe terrestrial erosion.

Before presenting and discussing the results of this research, information is provided on Saba island, the literature review on terrestrial erosion and the resulting impact on corals are portrayed, and the methods of the research are described.

1.1 Site description

Saba is a volcanic island located in the north-eastern Caribbean and has a surface area of approximately 13 square kilometres (figure 2 & 3) (De Palm, 1985). On the first of January in 2016, the island had 1947 inhabitants (CBS, 2017). Saba has very steep, instable slopes at the coast which are highly vulnerable to erosion as a result of sudden strong rainfalls, coastal development and the large amounts of goats who graze away the vegetation along the coast. Throughout the last decades, agricultural areas have diminished. However, land used for residents has strongly increased (De Freitas, Rojer, Nijhof & Debrot, 2016). Mount Scenery is with its 870.4 metres the highest peak of the island and is the top of the dormant volcano present on a 600 metres deep sea bottom (De Freitas et al., 2016).

Figure 2: Location map of Saba (Source: Google, SIO, NOAA et al., 2017)

Figure 3: Site map of Saba (Source: Google, SIO, NOAA et al., 2017)

Saba's warmest months are August and September and the coldest months are January, February and March. The average air temperature is 23.6 degrees Celsius in February and 26.5 degrees Celsius in September (1971-2000) (Meteorological Service of The Netherlands Antilles & Aruba, n.d.). The average water temperature throughout the year is 27 degrees Celsius (WaterTemperature.org, n.d.) Data of the Meteorological Department of Curacao (n.d.) shows several rainfall peeks throughout the year with the highest in November, reaching almost 140 mm of rainfall (figure 4). Saba experiences north-eastern trade winds resulting in predominantly east-northeast winds (De Freitas et al., 2016). The island has a hurricane season from June until December (NOAA, n.d.). The hurricanes have devastating effects on the vegetation on the island which strongly enhances the vulnerability to erosion (De Freitas et al., 2016). In addition, hurricanes can result in large waves which detach and shatter corals and which stimulate inflow of additional sediments that can abrade and bury corals (Rogers, 1993 & Mumby, 1999).

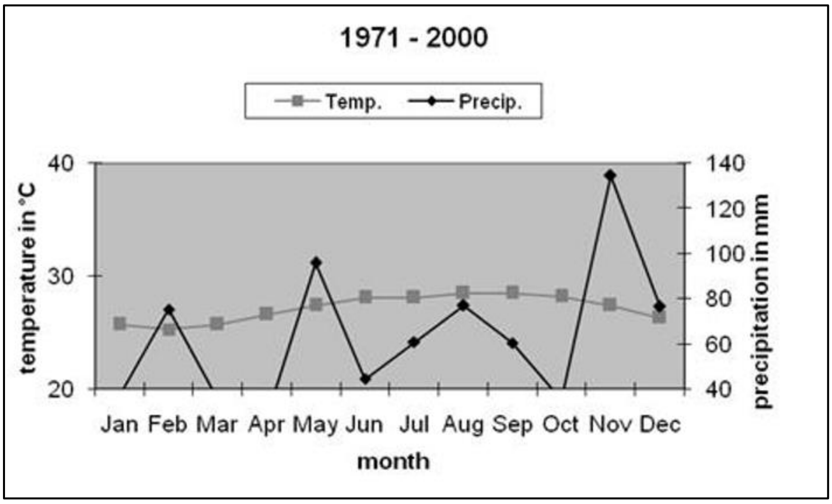

Figure 4: Climate diagram of Saba from 1971 up until 2000. (Source: Meteorological Department Curacao, n.d. & De Freitas et al., 2016)

2. Theoretical framework

As this research demands for a geo-ecological approach, knowledge is necessary of both the terrestrial processes that result in the flow of sediment as the processes that occur underwater that influence coral growth. This knowledge ensures substantiation for assessing the erosion intensity of the island, selecting sampling sites for data collection and selecting parameters which will be measured underwater. In order to gain this knowledge a literature review is conducted.

2.1 Origin and transportation of erosion material

Terrestrial erosion at the coast refers to the loss of landmass into the sea when soil and stone is gradually damaged and removed as a result of natural processes and anthropogenic interference (Bio et al., 2015 & Cambridge Dictionary, n.d.). Natural processes include river flows, storms, winds and waves. Examples of anthropogenic interference include construction, deforestation and agricultural practices (Karamage et al., 2016 & Bio et al., 2015). Erosion at the coast depends on both the off and the on-shore environment (Archetti & Zanuttigh, 2010 & Granja & Pinho, 2012). The sediment that enters the water is in most cases not all produced at the coast itself. Erosion processes upstream or on top of slopes inland can supply a great amount of the sediment deposited in oceans or lakes (Oleson, et al. 2016).

In order to gain insight in the expected severity of erosion, the erosion intensity, of an area, both soil erodibility and soil protection need to be taken into account (PAP & FAO, 1997). Soil erodibility refers to the ability of a soil to withstand erosion. This ability depends on physical characteristics of the soil such as the texture, permeability, structure and organic matter. Resistance to erosion is optimal when an improved soil structure is present in combination with a high concentration of organic matter and a fast infiltration rate. Consequently, silt, very fine sand and clay-textured soils are generally more vulnerable to erosion than sand, sandy loam and loamy soils (Ritter, 2015). Furthermore, fine grained silt and sandy soils are vulnerable to wind erosion. As a result of wind, soil particles get displaced. The finest particles are suspended into the air and transported over great distances. Bigger soil particles are lifted up for a short distance and fall back to the surface (saltation), or in the case of a coastal slope, sometimes into the ocean. When particles are too large to be lifted, winds will allow them to roll over resulting in surface creep. Both surface creep and saltation can result in abrasion and the dislodgement of more soil and stable aggregates. This leads to a further increase in the severity of erosion of the soil (Ritter, 2015). In addition, by studying Hjulström's curve, which combines sediment particle size with water velocity (Hjulström, 1935), it becomes clear that material with a texture of fine sand (100 μ) is most easily displaced by runoff, as smaller clayey material is attracted to itself and therefore sticky. Bigger coarser material can only be dislodged at higher flow rates since it weighs more. Consequently, when only texture is taken into account, soils that are rich in fine sand and loam are the most vulnerable to water erosion (FAO, 1996). In addition to the physical characteristics of the soil, the slope also has a strong influence on the erodibility of the soil. A steep and long slope has a higher risk of being eroded than a short gradual slope (Kinnell, 2000). In addition, at coasts, strong waves can result in abrasion and removal of coastal material such as rocks and soil (Granja, Pinho & Mendes, 2014).

Furthermore, soil loss due to soil erosion depends strongly on the amount of soil protection, which comprises both the type of land use and the percentage of soil cover (Cyr, Bonn & Pesant, 1995). Suescún et al. (2017) showed that natural forests have a very high regulation for potential precipitation-runoff-erosion-nutrient losses. In contrast, pastures and croplands show very high runoff and erosion losses. In addition, when fields are bare, they become more vulnerable to erosion (Cyr, Bonn & Pesant, 1995). Most of the wilderness areas on Saba are overly populated by goats which strongly enhances the vulnerability of these areas to erosion. Grazing lowers the resilience of the natural vegetation and disturbs natural succession. The highest densities of goats are present at the vulnerable arid coastal areas on the western and southern parts of the island. These areas are open and hold shrubby vegetation with poor soil conditions. If the amount of goats would be reduced, it is expected that these areas will be able to develop evergreen woodland, similar to the northern part of the island. This recovery of vegetation will strongly reduce the vulnerability to soil erosion (de Freitas, Rojer, Nijhof & Debrot, 2016).

Protection provided by vegetation cover is one of the most important factors influencing the risk of erosion (Cyr, Bonn & Pesant, 1995 & Norder et al., 2017). The presence of plants and residue cover helps to protect the soil surface against water impact by rainfall. In addition, it slows down the movement of the runoff, allowing for excess water to infiltrate into the soil. Therefore, when very little or even no vegetation is present, the amount of erosion of the soil increases. The type, quantity and extent of vegetation cover strongly influences the erosion reducing power. When the soil is completely covered by vegetation and residues and the falling rain is intercepted, protection against soil erosion is most effective. When surface water can enter the soil, for instance through residual root-channels, soil erosion is also reduced. In addition, how effective the vegetation cover is in preventing erosion also depends on the amount of protection present throughout the year (Ritter, 2015). It is therefore expected that evergreen forests, which have leaves all year round, form a higher protection for the soil than deciduous forests, as they also experience seasons without leaves.

2.2 Impact of sediment on coral

When the terrestrial runoff and erosion products produced by waves enters the coral reefs, the sediment can influence the corals through consequences of sedimentation and by effects resulting from increasing turbidity (Fabricius, 2005).

The extent of the consequences of sedimentation, the process of being deposited as a sediment (Oxford Dictionaries, n.d.), greatly depends on the severity of the sediment inflow, sediment type, coral species and environmental conditions (Fabricius, 2005). High sedimentation rates, quantified as accumulating to more than 100 mg dry weight cm^{-2} deposits, can easily smother benthic life and exposed coral tissue can be killed within a few days (Riefel & Branch, 1995 & Golbuu, Victor, Wolanski, & Richmond, 2003). When lower sedimentation levels occur (less than 100 mg cm^{-2}) photosynthesis productivity in corals lowers (Philipp & Fabricius, 2003).

Hodgson (1990) and Hodgson and Walton Smith (1996) assessed the impact of sediment inflow from logging in the Philippines. The inflow led to a decline in coral cover and inhibition of coral settlement. In addition, the biodiversity decreased as a result of the disappearance of species that are sediment-sensitive. This occurred within a year. Cortés and Risk (1985) found that sedimentation at two sites in Costa Rica resulted in low alive coral cover and a low species diversity. In addition, by measuring the sizes of *Agaricia agaricites, Porites astreoides* and *Siderastrea radians* colonies, it was found that sedimentation resulted in a larger average colony diameter. Furthermore, the skeletons of corals in exposed reefs had high acid-insoluble residues incorporated affecting their health.

Moreover, sedimentation results in fewer coral species and less alive coral through abrasion and reduced calcification resulting in slower rates of accretion of reefs (Roger, 1990, Hubbard, 1997 & Segal & Castro, 2011). However, corals have several active and passive techniques to cope with sediment. In example, they use their tentacles and cilia or they entangle particles in mucus which later detach from the colonies surface (Hubbard, 1997). Coral growth may decrease when its energy is used for the removal of sediment. Strong currents can help to remove sediment particles which saves the coral energy (Rogers, 1990). As a result of differences in morphology, not every coral species has the same strategy to reject sediment (Hubbard & Pocock, 1972). For example, *Agaricia agaricites* changes its orientation as adaptation to sedimentation stress and steep angles of the large calyx of *Scolymia cubensis* can be an adaptation to stimulate sediment removal (Bak & Elgershuizen, 1976 & Logan, 1988).

Rogers (1983) found that *Acropora palmata*, the species also studied in this research, is vulnerable to sedimentation as particles accumulate on flat parts of the colony. Calcareous sediments were applied in situ to several coral species and *Acropora palmata* appeared to be the most sensitive. Applying only 200 mg cm^{-2} already resulted in death of the underlying tissue. Bak and Elgershuizen (1976) concluded that *Acropora palmata* is a highly ineffective sediment remover and is not able to remove particles of any size without the help of wave action.

Furthermore, Philipp and Fabricius (2003) state that sedimentation stress in coral colonies increases linearly with the amount of sedimentation and the duration. This means that a specific amount of sediment that is deposited on coral tissue for one time unit imposed the same stress as twice this amount deposited for half the time unit.

Moreover, wave action and current influence the distribution of the sediment and can diminish the consequences of sediment inflow. Most species cannot persist in regions that are wave-protected and where silty and nutrient rich sediments are deposited. More species will be able to persist in areas that are wave-exposed or with coarse grained or nutrient-poor sediments (Fabricius, 2005).

When large amounts of sediment are added, water becomes more turbid. As a result, light reduction my occur. Many research has been done about this indirect consequences of sediment input, in which light availability decreases. Walker and Ormond (1982) and Anthony and Fabricius (2000) state that shading results in reduced calcification as corals and the zooxanthellae strongly depend on light availability for deposition of calcium carbonate (Chalker, 1981). Anthony and Fabricicus (2000) found that this reduction occurs after approximately four weeks of exposure. In addition, increased mortality, reduced species richness, changes in in coral community structure and life forms, reduced net primary productivity, thinner tissue and compressed depth zonation may occur as a result of turbidity (Loya, 1976, Rogers, 1979, Acevedo & Morelock, 1988, Fabricius & De'ath, 2001 & Crabbe & Smith, 2002).

Light availability decreases as a function of water depth and particle concentration. However, it also depends on the characteristics of the suspended particles (Te, 1997*).* Fine clay and organic particles can suspend either from the seafloor or from entrance as terrestrial runoff. The particles undergo cycles of deposition and resuspension and consequently light will be reduced for a protracted time (Abal & Dennison, 1996). If there is an increased nutrient runoff, phytoplankton production is amplified which can also reduce light availability by increasing the turbidity. The consequences of turbidity rise with increasing depth and some even state that these effects are minimal in shallow water. However, the impact varies strongly among different species (Fabricius, 2005).

3. Methods

3.1 Potential erosion intensity mapping

In order to assess how the severity of terrestrial erosion is distributed among the coast of Saba, an potential erosion intensity map was created. This map visualises the assumed erosion risk of terrestrial Saba by combining basic land surface parameters, such as the soil type, that influence soil erosion. It can be considered as a predictive phase in which preliminary assumptions can be made on erosion risk. The map was created using the ArcMap 10.4.1 software and the methods were based on the PAP and FAO guidelines for mapping rainfall-induced erosion processes in the Mediterranean coastal areas (PAP & FAO, 1997). Raster calculations with specific matrixes adapted to the local environment were used to integrate erodibility and soil protection scores to form erosion intensity scores (figure 5). For all the maps created the coordinate system WGS 1984 UTM Zone 20N was used. The erodibility scores were calculated by combining preliminary data of slope and soil types. Slope data was created with the use of a DEM (Digital Elevation Model) from the SCF (n.d.(a)) and the soil type data was created with the use of data from Koomen, Van Dorland and Makaske (2012). The soil protection scores were calculated by using a combination of land use data from Smith, Mücher and Debrot (2014) and vegetation cover data from DCBD (2014). A more detailed description of the methods applied to create the potential erosion intensity map is given in Appendix A.

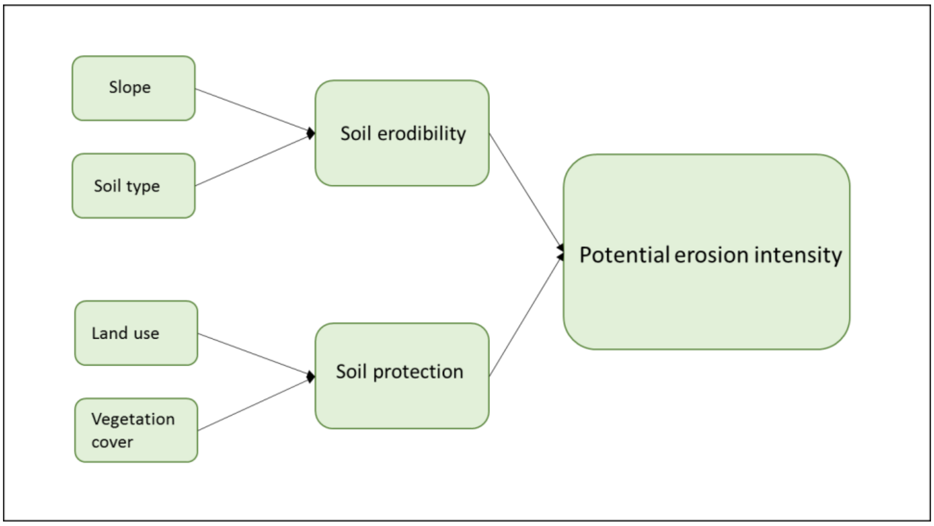

Figure 5: Simplified overview of the creation process of the potential erosion intensity map

Following the guidelines of the PAP and the FAO leads to a map indicating five different classes of erosion intensity. The most important adjustment applied to these guidelines was the addition of two extra erosion intensity classes. This addition was done since the use of five classes resulted to be insufficient. For this research the differences in erosion intensity of the coastal areas is relevant and with five classes the whole coast was classified in the same, most extreme, erosion intensity class. Adding two extra classes made it possible to distinguish between the erosion intensity of different coastal areas.

3.2 Selecting sampling sites for underwater assessment

Of the seven classes present in the potential erosion intensity map, only the three most severe ones occur at the coast, namely very high, extremely high and most extreme. These three classes are called erosion intensity class 1, 2 and 3 and were used to investigate to what extent terrestrial erosion processes influence the site conditions of elkhorn on Saba. For every class at least five sampling sites were selected where dives were conducted. The selection of these sampling sites was based on the potential erosion intensity map and was influenced by weather conditions and time restrictions. Eventually dives at 16 different sites where conducted (table 1 and figure 6).

Table 1: The 16 selected sampling sites

ID	Sampling site name	Coordinates
1	Ladder Labyrinth (white mooring)	N17◦37.630' W063◦15.540'
2	Rays n' Anchors	N17◦37.381' W063◦15.571'
3	Green Island (next to the shore)	N17◦38.919' W063◦13.842'
4	Main nursery	N17◦38.235' W063◦15.376'
5	Donna Mae	N17◦36.821' W063◦14.943'
6	Torrens Point	N17◦38.609' W063◦15.197'
7	Ladder Labyrinth (red mooring)	N17◦37.523' W63◦15.567'
8	Big Rock Market (white mooring)	N17◦36.750' W063◦14.186'
9	Cave of Rum Bay (inlet)	N17◦38.733' W063◦15.024'
10	Cave of Rum Bay (outer point)	N17◦38.758' W063◦15.126'
11	Great Point	N17◦39.142' W063◦14.517'
12	Core Gut Bay	N17◦37.841' W063◦13.079'
13	Gary's pond	N17◦36.874' W063◦14.696'
14	Hole in the Corner	N17◦37.070' W063◦13.579'
15	Great Hole	N17◦38.801' W063◦13.145'
16	Hot Spring (North)	N17◦38.829' W063◦13.629'

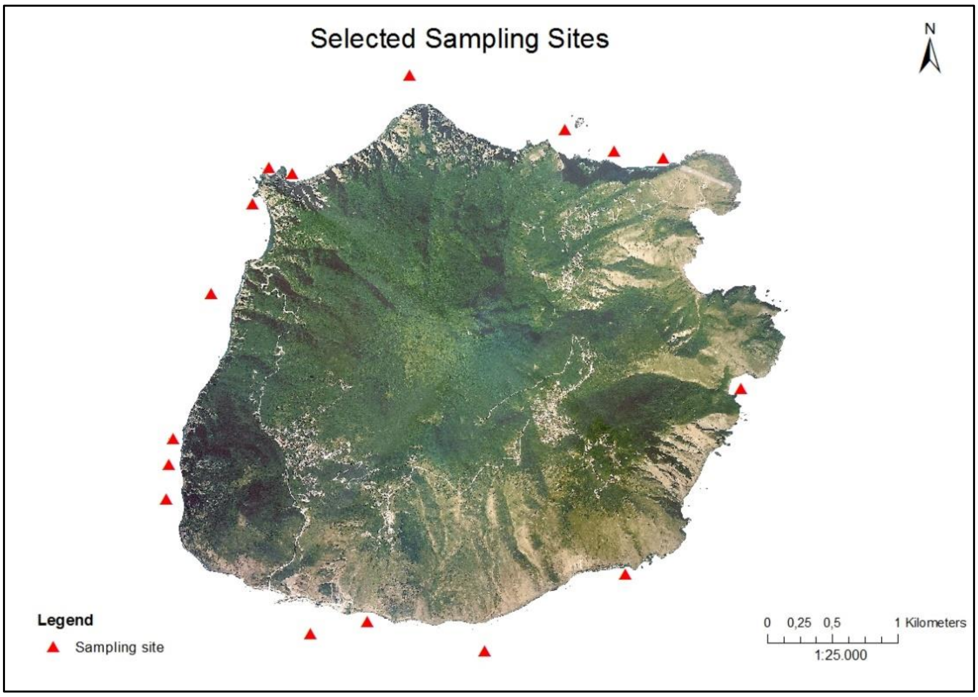

Figure 6: The sampling sites selected for the fieldwork on Saba (Source: SCF, n.d.(b). Adapted by A.E. Mulder)

Since the erosion processes can vary strongly in a small area, it was expected that not every sampling site is classified in the correct erosion intensity class. In order to exclude this type of error from the research, guidelines were set to visually inspect and identify the different erosion intensity classes (table 2). These guidelines were created by visiting sampling site that were located in larger areas that were completely classified in the same class. This technique provided an overview of how the three different classes of erosion intensity can be described and what the observed differences are between them. Criteria included were vegetation, slope and terrestrial material present. Big rocks are believed to have a positive influence on elkhorn occurrence as they do not influence the turbidity and provide a suitable substrate for coral colonies to settle (Van Katwijk, 1993). It is expected that the higher the erosion intensity, the more sediment will enter the coral reef ecosystem.

Table 2: Guidelines for classifying the erosion intensity into three different levels (Source: photos by A.E. Mulder)

Class name	Description	Visual example
Very high (erosion intensity 1)	Relatively gentle slopes with high percentages of vegetation cover (>50%). **Or** Solid rock with no loose materials. Erosion product will be big rocks.	 
Extremely high (erosion intensity 2)	Far less vegetation cover (<50%), but still present. More smaller clasts visible (cross section < 10 cm) that could be displaced and translocated to the ocean.	
Most extreme (erosion intensity 3)	Very little to no vegetation present (<10%). Mostly steep slopes and high amounts of loose sediment (cross section < 1 cm) and/or alluvial vans of sediment present.	

3.3 Collecting habitat and colony data

At every sampling site it was first checked whether the location was correctly classified. This was done by using the created guidelines during the on-site assessment. Pictures of the slope were made, the GPS sampling site was tracked and the transparency was assessed with the use of a secchi disk. Hereafter a dive of approximately 40 minutes was conducted in which the habitat lying under the slope was examined. First pictures of the habitat were made and the habitat was briefly described on a slate. Hereafter, habitat parameters were measured (table 3). In the remaining dive time elkhorn colonies were searched by swimming a zigzag pattern parallel to the shore, between depths of three and eight meters. The zigzag pattern started parallel to the shore and then turned 30 degrees towards the shore. After two minutes it turned 60 degrees away from the shore, resulting in a direction of 30 degrees in the direction of the deeper ocean. When a colony was found, pictures were taken and the parameters presented in table 4 were measured.

Table 3: The habitat parameters measured at each sampling site

Habitat parameter	Unit	Description
Elkhorn present	-	Indication if any elkhorn is detected in the area. Yes (1) or no (0).
Abundance	-	Abundance of elkhorn colonies. 0 (absent), 1 (few), 2 (common), 3 (abundant).
Current	-	Presence of a current classified in three groups: 1=no current, 2=mild current, 3=strong current.
Wave action	-	Presence of wave action. Yes (1) or no (0).
Total dead surrounding	%	The percentage of the total observed colonies that is completely dead. The range is 0-100% with increments of 5%.

Table 4: Parameters measured at each elkhorn colony

Colony parameter	Unit	Description
Depth	m	The depth of the colony. Measured at the middle of the colony using a Suunto Zoop Novo dive computer.
Temperature	˚C	The temperature at the colony. Measured using a Suunto Zoop Novo dive computer.
Substrate	-	The substrate that the colony is located on, classified in three groups: 1=cemented sand, 2=rock, 3=dead colony.
Slope angle	◦	The angle of the most dominant slope the colony has with its substrate. This parameter is estimated during the dive and later checked with the use of pictures and a protractor triangle. The range is 0-90◦ with 5◦ increments.
Relative position	m	The elevation of the colony relative to the surrounding ground. Measured using a Suunto Zoop Novo dive computer.
Cover of sediment	-	Indication if sediment is present on the alive tissue of the colonies surface. (Yes or no.)
Dead coral tissue	%	Percentage of the colony that is dead. Estimated during the dive and later checked by examining the pictures made. The range is 0-100% with increments of 5%.
Cross section largest	cm	Length of the largest cross section of the colony. Measured during the dive with a foldable ruler.
Cross section perpendicular	cm	Length of the cross section perpendicular to the largest cross section. Measured during the dive with a foldable ruler.

The parameters were selected based on the conducted literature research provided in the theoretical framework. They covered the abiotic factors of the habitat, which are directly influenced by influx of sediment and easily measurable. In addition, the parameters assessed the state of the colonies themselves. Furthermore, the parameters were inspired on research by De'ath and Fabricius (2000) who examined the relation between abundance of soft coral taxa and physical and spatial environmental information. If no colonies were observed, the temperature of the water was measured at the end of the dive.

3.4 Analysis of results

The data was analysed with the use of R software and the R studio package (R Core Team, 2017). First, scatter plots with a Loess smooth curve were created to explore the data and to detect relations between the different variables. Hereafter, GLM's (Generalised Linear Model) and LM's (Linear Model) with binomial or gaussian distributions were fit to the data. This method allowed for assessment of the effect terrestrial erosion has on the individual parameters. In addition, fitted models that include the different levels of erosion intensity were compared with nested models excluding erosion intensity to determine if the effect that erosion imposes on the parameter is significant.

Furthermore, GLM and LM regression was conducted in which erosion intensity predicts the probability of elkhorn occurrence and in which erosion intensity predicts the percentage of the total observed colonies in a habitat that are dead. It should be noted that this type of regression is theoretically not suitable for this data, as it is unknown if the difference in severity between erosion intensity class 1 (very high) and 2 (extremely high) is identical to the difference between 2 (extremely high) and 3 (most extreme). However, the regression made it possible to predict probabilities of elkhorn occurrences at sampling sites that fall in between the specified erosion intensity classes. Therefore, by fitting this type of model, the assumption was made that the differences in severity of terrestrial erosion between the erosion intensity classes are equal.

4. Results

4.1 Potential erosion intensity map

The resulting potential erosion intensity map shows that terrestrial erosion is predicted to be the most severe at the coast and decreases land inwards. In addition, only the three most severe erosion intensity classes occur at the coast (figure 7).

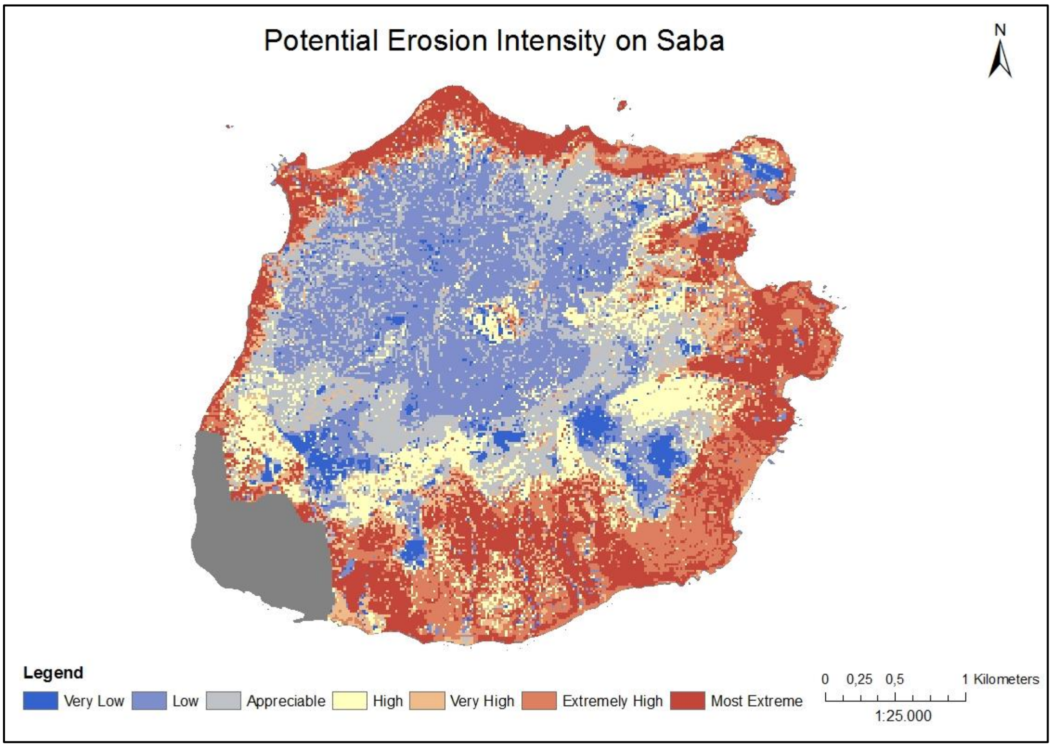

Figure 7: Potential erosion intensity map of Saba created by the integration of the level of erodibility and the level of soil protection (created by A.E. Mulder)

4.2 Habitat characteristics

Elkhorn colonies were present at 100 percent (5 locations) of the sampling sites with erosion intensity class 1 (very high), at 67 percent (four locations) with erosion intensity class 2 (extremely high), and at 40 percent (two locations) with erosion intensity class 3 (most extreme) (table 2). The GLM using ANOVA and a binomial distribution (*Elkhorn present ~ Erosion intensity-1*) indicated that increase of intensity of terrestrial erosion is associated with a decrease in the probability of elkhorn occurrence (figure 8 & Appendix B).

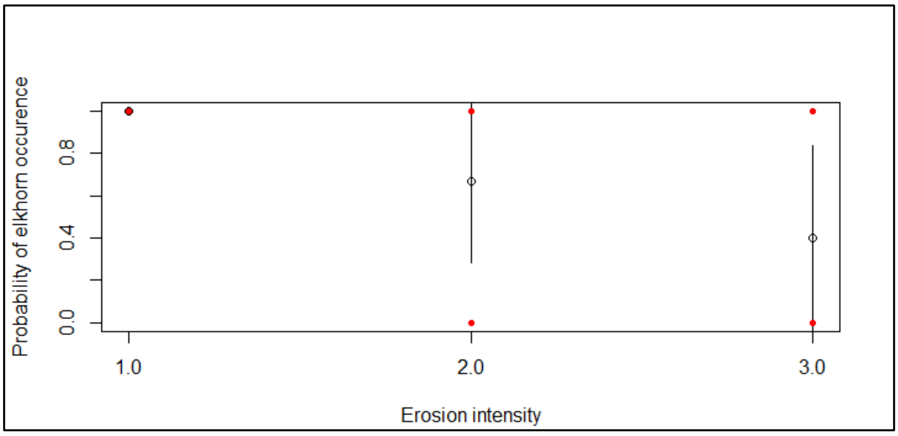

Figure 8: A GLM (*Elkhorn present ~ Erosion intensity -1*) fitted to predict probability of elkhorn occurrence by erosion intensity. Erosion intensity 1= very high, erosion intensity 2= extremely high, erosion intensity 3=most extreme. The means are given with their 95% confidence interval. The data points are given as red dots (n=16).

The effect of erosion on elkhorn presence is assessed by an ANOVA comparing two GLM's with binomial distributions. In the first model (*Elkhorn present ~ Erosion intensity*) erosion is included. The second model is the nested model (*Elkhorn present ~ 1*). Comparison of the two models with a one sided test shows that the negative effect of erosion on elkhorn occurrence on Saba is significant (p=0.032), using a level of significance of 0.05 (n=16). The first model, in which the erosion intensity is included, has a lower AIC (Akaike Information Criterion) which indicates a better fit to the data than the nested model.

A GLM regression with a binomial distribution and a logit transformation gives an intercept of 4.64 and a slope of -1.75 (*Elkhorn occurrence = 4.64 - 1.75 * Erosion intensity*). In this model erosion intensity is considered as a numeric variable instead of a factor. The p value indicating the probability that the slope differs from zero is 0.069, demonstrating no significant effect of erosion on the probability of elkhorn occurrence in a two-sided test (n=16). However, a one-sided test is suitable as the hypothesis comprises that the effect of erosion on elkhorn occurrence is negative. The p-value of the one-sided test is obtained by dividing the p-value of the two-sided test in half. The resulting p-value of 0.034 again shows that the negative effect of erosion on elkhorn occurrence on Saba is significant (figure 9 & Appendix B).

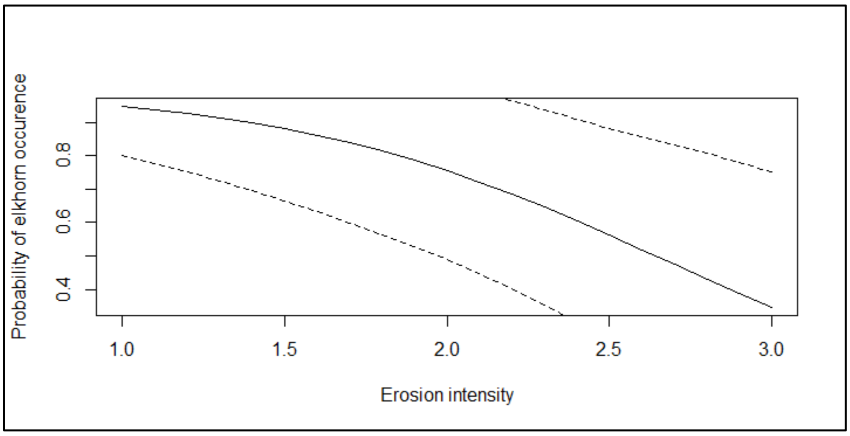

Figure 9: GLM regression of erosion intensity predicting the probability of elkhorn occurrence. The data is back-transformed since a logit transformation was used for the regression. The 95% confidence interval is given by the dotted lines. Erosion intensity 1= very high, erosion intensity 2= extremely high, erosion intensity 3=most extreme. (n=16).

The most occurring abundance classes were 'few' and 'common' for erosion intensity class 1 (very high), 'abundant' for erosion intensity class 2 (extremely high) and 'absent' for erosion intensity class 3 (most extreme) (table 5).

Table 5: The abundance of elkhorn colonies under different coupled severities of terrestrial erosion (n=16)

Abundance> / *Erosion intensity˅*	**Absent**	**Few**	**Common**	**Abundant**
Very high (1)	0%	40%	40%	20%
Extremely high (2)	33%	17%	0%	50%
Most extreme (3)	60%	20%	0%	20%

A LM with a gaussian distribution and log transformation fitted to the data (*Total dead surrounding ~ Erosion intensity-1*) showed a connection between erosion intensity and the percentage of colonies in a habitat that is dead (figure 10). The mean percentage of colonies that is dead is 66 percent at the lowest erosion intensity (very high), 75 percent at the middle erosion intensity (extremely high) and 85 percent at the highest erosion intensity (most extreme). This suggests an increase in the percentage of the colonies that is dead when terrestrial erosion increases. However, an ANOVA comparing the model (*Total dead surrounding ~ Erosion intensity*) to the nested model (*Total dead surrounding ~ 1)*, indicated that this effect of erosion is not significant in both a two-sided test (p= 0.45) and a one-sided test (p= 0.23, n=11).

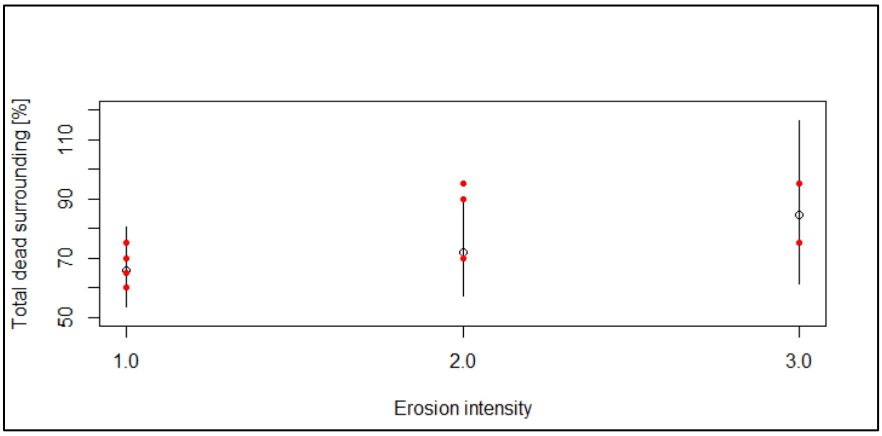

Figure 10: The back-transformed LM predicting the percentage of all the colonies observed in the habitat that are dead by the erosion intensity. The means are given with their 95% confidence interval. Erosion intensity 1= very high, erosion intensity 2= extremely high, erosion intensity 3=most extreme. The data points are given as red dots (n=11).

A LM regression with a log transformation and a gaussian distribution (*Total dead surrounding ~ Erosion intensity*) also indicated that the effect of erosion on the percentage of colonies that is dead is not significant (p= 0.20, n=11). However, when plotting the back-transformed results of the fitted model, it can be assumed that a relation is present in which the percentage of the coral colonies in the habitat that is dead increases when the severity of erosion increases (figure 11).

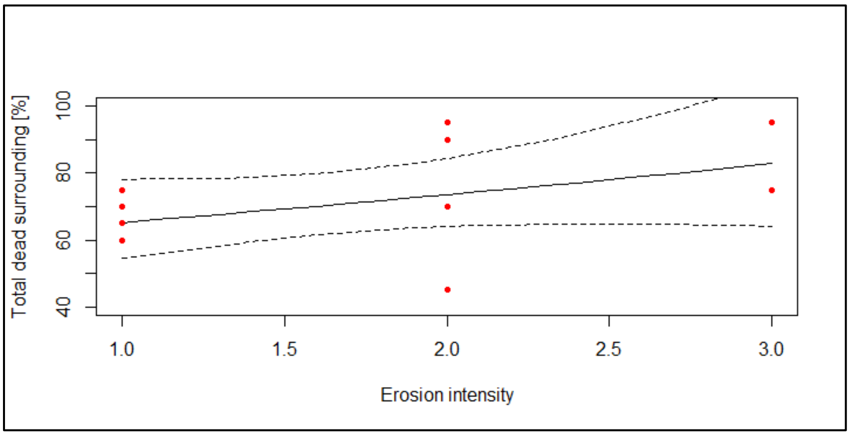

Figure 11: LM regression of erosion intensity predicting the percentage of colonies in the habitat that is dead. The data is back-transformed as a log transformation was used for the regression. The 95% confidence interval is given by the dotted lines. Erosion intensity 1= very high, erosion intensity 2= extremely high, erosion intensity 3=most extreme. The data points are given as red dots (n=11).

Furthermore, a current was only present at one sampling site, namely, at Great Point. At this sampling site elkhorn was abundant and the lowest erosion intensity class that occurs at the coast was present (very high). At 100 percent of the sampling sites where elkhorn was present, wave action was also present (n=11). Wave action was detected at two out of the five sampling sites without elkhorn. The erosion intensity classes of these sampling sites were 2 (extremely high) and 3 (most extreme). At one out of three sampling sites with the most severe erosion class (most extreme) wave action was present but elkhorn was absent.

At 75 percent of the sampling sites the bottom was visible when the vertical transparency was measured with a secchi disk (n=16). The bottom was visible at all the sampling sites (5 locations) with erosion intensity class 1 (very high), at 67 percent (4 locations) of the sampling sites with erosion intensity class 2 (extremely high), and at 60 percent (3 locations) of the sampling sites with erosion intensity class 3 (extremely high). The mean depth at which the vertical visibility was measured at erosion intensity class 1, 2 and three were 8.34 (m), 10.62 (m) and 10.14 (m) respectively.

4.3 Colony characteristics

In total, 78 colonies were measured, of which 34 at sampling sites with erosion intensity class 1 (very high), 31 at sampling sites with erosion intensity class 2 (extremely high) and 13 at sampling sites with erosion intensity class 3 (most extreme). An overview of the means of the numeric measured colony parameters per erosion intensity class is given in table 6.

Table 6: Mean values of the numeric measured colony parameters per erosion intensity class.

Erosion intensity> *Colony parameter˅*	**Very high (1) (n=34)**	**Extremely high (2) (n=31)**	**Most extreme (3) (n=13)**
Dead coral tissue [%]	11	17	22
Relative position [m]	2.56	2.67	2.39
Depth [m]	5.39	7.06	4.75
Slope angle [◦]	22.94	16.61	20.00
Cross section [cm]	132.44	120.35	126.00
Cross section perpendicular [cm]	81.82	81.23	82.85

On average 15 percent of the tissue of the measured colonies is dead (n=78). The mean amount of dead coral tissue increases as the erosion intensity increases (from 11% to 22%) (table 6). An ANOVA with a gaussian distribution comparing two linear models (*Dead coral tissue ~ Erosion intensity* and *Dead coral tissue ~ 1)* shows that the effect of erosion on the percentage of the dead tissue of a colony is not significant in both a two-sided test (p=0.26) and a one-side test (p=0.23) (n=78) (Appendix B). However, the RSS (residual sum of squares) of the model in which erosion is included is smaller than the RSS of the nested model, indicating a better fit to the data when erosion is included.

Furthermore, the mean elevation of a colony relative to its surrounding was 2.58 meters (n=78). The mean relative position of the colonies at different levels of erosion intensity are very similar and have highly overlapping confidence intervals, suggesting no direct effect of erosion on the relative position of the colonies (table 6 & Appendix C). However, a scatter plot of with a Loess smooth curve (figure 12) suggest a decrease in dead colony tissue if the colony is located more than four meters higher relative to its surrounding and when terrestrial erosion is extremely high (erosion intensity 2) or most extreme (erosion intensity 3). A LM with a gaussian distribution (*Dead coral tissue ~ Erosion intensity * Elevation),* in which the binomial parameter *Elevation* indicated if the relative position was higher (1) or lower (0) than four meters, suggested that, at erosion intensity class 1 (very high) being elevated more than four meters does not have a strong influence on the percentage of colony tissue that is dead. However, at erosion intensity level 2 (extremely high) a decrease of 18 percent and at erosion intensity class 3 (most extreme) a decrease of 26 percent of dead colony tissue is predicted when the colony's position is more than four meters higher than its surrounding (Appendix B). Nevertheless, the coefficients were not significant (p>0.05, n=78). An ANOVA comparing two linear models with a gaussian distribution (*Dead coral tissue ~ Erosion intensity + Relative position + Erosion intensity: Relative position* and *Dead coral tissue ~ Erosion intensity + Relative position*) estimated the effect of the interaction between erosion intensity and relative position to not be significant (p=0.31, n=78). However, the RSS of the model including the interaction was smaller than the model without the interaction, suggesting a better fit to the data of the model including the interaction. Predictions from the results of the model which includes the interaction between relative position and erosion intensity, suggests that the higher the erosion intensity level and therefore the stronger the terrestrial erosion, the stronger the link between elevation and coral tissue death (figure 13).

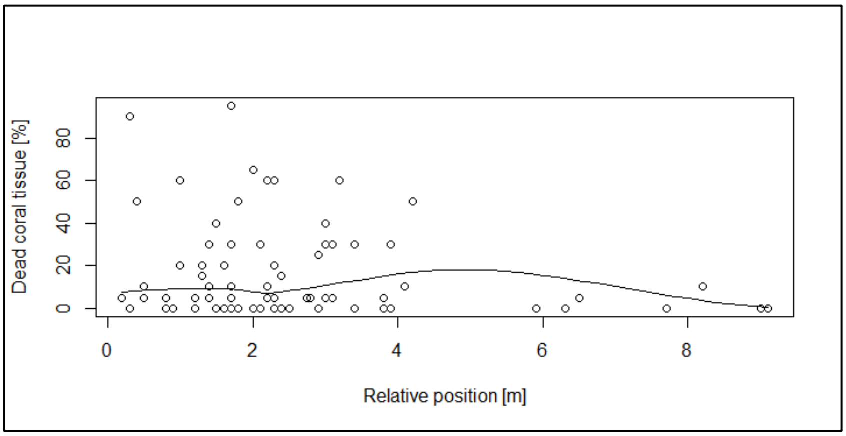

Figure 12: Scatter plot of relative colony position and dead colony tissue with a smooth curve fitted by Loess. De data points are given as hollow dots (n=78).

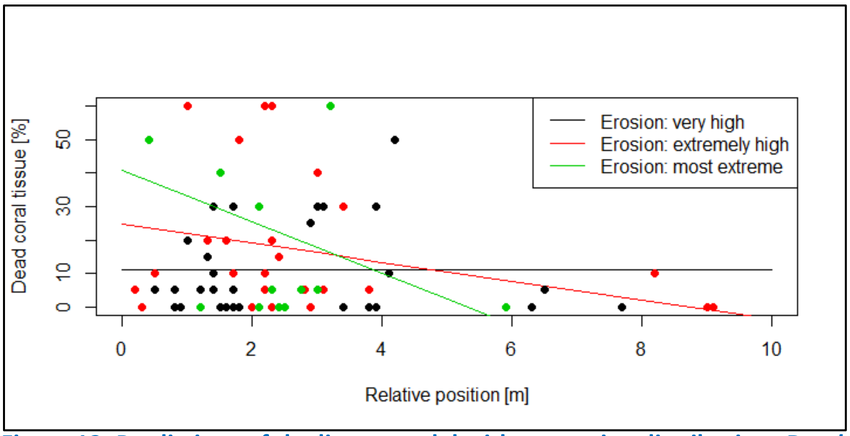

Figure 13: Predictions of the linear model with a gaussian distribution: *Dead coral tissue ~ Erosion intensity + Relative position + Erosion intensity: Relative position, allowing for different slopes for each group.* The data points are given as coloured dots (n=78).

The average depth of all the colonies was 5.95 meters (n=78) (figure 6 & 14). A LM with a gaussian distribution (*Colony depth ~ Erosion intensity*) indicated that the depths of the colonies at erosion intensity class 2 is different from the depths of erosion intensity class 1 and 3. An ANOVA with a gaussian distribution comparing two models *(Angle of slope ~ Colony depth* & *Angle of slope ~ 1*) indicates that there is indeed a significant difference between the means of the three groups in this data (p=0.00014).

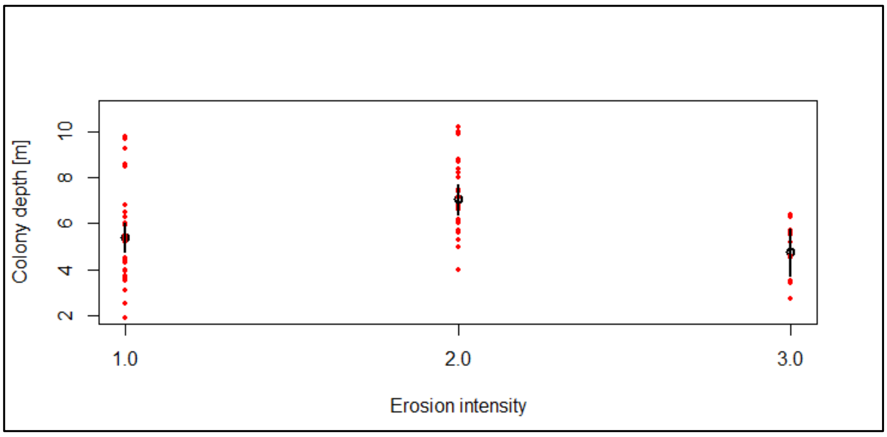

Figure 14: The colony depth at different erosion intensity classes. The 95% confidence interval is included. Erosion intensity 1= very high, erosion intensity 2= extremely high, erosion intensity 3=most extreme. The data points are given as red dots (n=78).

The most occurring substrate on which the colonies are located is rock (68%, 53 colonies). 29 percent (23 colonies) of all the colonies is located on an old dead colony and 3 percent (2 colonies) is located on cemented sand. This distribution is similar for the different levels of erosion. However, when the highest level of erosion is present, the percentage of the colonies located on a dead colony is considerably larger than at the other two lower classes of erosion (table 7).

Table 7: The substrate of colonies under different coupled severities of terrestrial erosion (n=78)

Substrate class> / *Erosion intensity^V^*	**Cemented sand**	**Rock**	**Dead colony**
Very high (1)	0.0%	70.6%	29.4%
Extremely high (2)	6.5%	71.0%	22.6%
Most extreme (3)	0.0%	53.8%	46.2%

The 'Water temperature' and 'Cover of sediment' parameters showed almost no variation. A temperature of 27 degrees Celsius was present at all of the colonies except for five at Torrens Point, where 28 degrees Celsius was measured. At all the sampling sites where no elkhorn was present, the water temperature was also 27 degrees (5 locations). None of the alive tissue of the colonies measured was covered in sediment.

Furthermore, the average angle of the most dominant slope the colonies had with its substrate is 19.94 degrees. The means of this parameter at different erosion intensity classes are very similar (table 6), and an ANOVA with a gaussian distribution comparing a model (*Angle of Slope ~ Erosion intensity*) with its nested model (*Angle of slope ~ 1*) indicated that the effect of erosion on the angle of the slope is not significant (p=0.48, n=78) (Appendix B & C).

The parameters 'Cross section largest' and 'Cross section perpendicular' have a Pearson correlation coefficient of 0.78. This is rather close to one, suggesting the two variables are positively linearly related. The means of 'Cross section largest' and 'Cross section perpendicular' for all the colonies are 126.56 cm and 81.76 cm respectively. As can be expected when observing the confidence intervals (Appendix C), an ANOVA with a gaussian distribution comparing two linear models with a gaussian distribution (*Cross section largest ~ Erosion intensity* & *Cross section largest ~ 1)* estimated the effect of terrestrial erosion on the size of the largest cross section to be not significant (p=0.78, n=78).

Furthermore, interactions between different parameters are detected when observing scatterplots with a Loess smooth curve. When colony depth increases, the angle of the most dominant slope de colony makes with its substrate decreases (figure 15). This relation appears to be present to a depth of six meters. A LM with a gaussian distribution was fitted and showed that the colony depth has a significant influence on the size of the most dominant slope angle (p=0.00087, n=78).

In addition, when the angle of the slope increases, the largest cross section decreases (figure 16). This effect is significant according to a LM with a gaussian distribution that was fitted to the data (p=0.0026, n=78) (Appendix B).

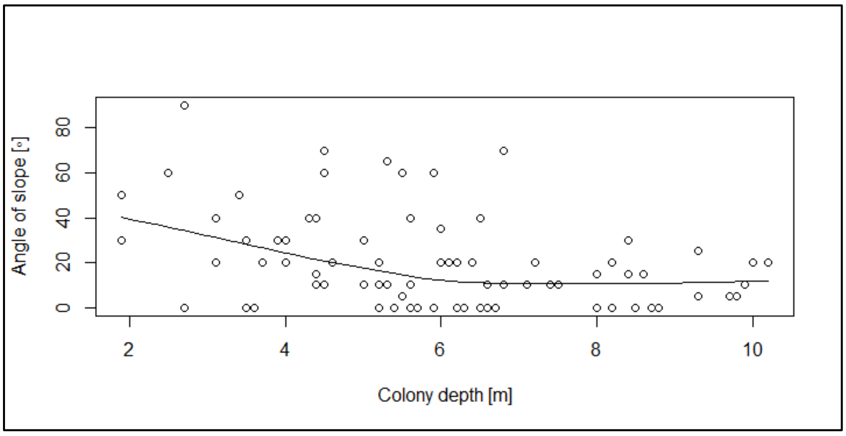

Figure 15: A scatter plot of colony depth and the angle of the most dominant slope the colony makes with its substrate is given with a smooth curve fitted by Loess. De data points are given as hollow dots (n=78).

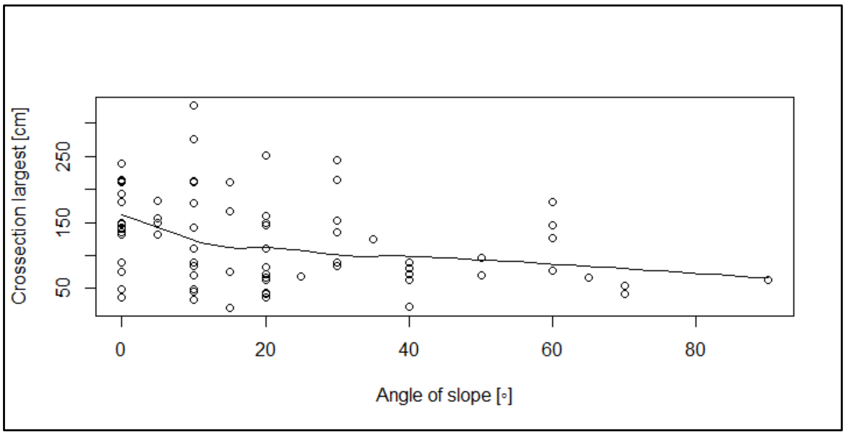

Figure 16: A scatter plot of the angle of the most dominant slope the colony makes with its substrate and the larges cross section of the colony is given with a smooth curve fitted by Loess. The data points are given as hollow dots (n=78).

5. Discussion

5.1 Discussion on the outcomes

5.1.1 Habitat parameters

It can be concluded that erosion has a significant negative effect on the probability of elkhorn occurrence. This correspond to the common perception in the literature that the influx of sediment results in a decline of coral cover (i.e. Hodgson (1990), Hodgson and Walton Smith (1996), Shimoda, Ichikawa, Matsukawa, 1998 & Oleson et al., 2017). GLM regression also shows an effect in which an increase in terrestrial erosion results in a decrease of the probability of elkhorn occurrence. However, it should be noted that this type of regression is theoretically not suitable for the data as it is unknown if the differences in erosion severity are equal between the different erosion intensity classes.

No influence of erosion is expected on the abundance of elkhorn as the abundance levels at the sampling sites of the different erosion intensity classes appear to be random. The category 'absent' increases when the erosion intensity increases. However the other categories, which indicate how abundant the colonies are when they are present, do not demonstrate to be affected by erosion severity in this dataset. Even though an effect of erosion on the probability of elkhorn occurrence is present, the erosion intensity does not influence how abundant the species is.

Furthermore, the mean percentage of dead colonies increases when the severity of terrestrial erosion increases. This implies that the erosion products entering the coral reef ecosystem on Saba result in colony death. This corresponds to Cortés and Risk (1985) who have concluded that sedimentation resulted in low percentages of living coral covers. Nevertheless, the effect on erosion on the percentage of dead colonies was not significant in the data. This can be a result of a too small sample size (n=11), as a small n reduces the power to detect a difference in the means of the different classes. However, it should be noted that erosion is not the only cause that can result in colony death. White band disease, anthropogenic damage, predators and ocean acidification are examples of other factors that can cause coral death which are not included in this research (Riegl, 1995, Meesters, Wesseling & Bak, 1997 & Lewis, 1997). It can also be possible that colonies become more vulnerable to other threats, such as diseases, when a high influx of sediment is present. In that case, erosion might not be the direct effect of colony death but it does enhance the chance of colony death indirectly.

A current was only present at one sampling site. Even though elkhorn was abundant at this sampling site, the too small sample size ensures that no conclusions can be drawn on the influence of currents on elkhorn occurrence and it cannot be assessed if a current reduces the negative consequences of sediment inflow.

At 100 percent of the sampling sites where elkhorn was present, wave action was also present, and at 60 percent of the sampling sites where elkhorn was absent, wave action was also absent. This suggests that wave action is essential for elkhorn growth. However, it is not the case that wave action is the only determining factor for elkhorn occurrence as at 12.5 percent of the sampling sites (2 locations) wave action was present, but elkhorn was not. At these sampling sites the erosion intensity class was 2 (very high) or 3 (extremely high). Therefore the factor determining that elkhorn was absent might be erosion in these situations. However, the sample size was too small to statistically test this assumption.

Furthermore, it was observed that the chance to see the bottom as a result of a good visibility decreased as the erosion severity increased. However, these transparencies were measured at different depths ranging from 14.8 to 5.0 meters. As a result, sampling sites where the bottom was not visible were sometimes a few meters deeper than sampling sites where the bottom was visible. Consequently it is impossible to compare the sampling sites and to analyse the parameter in an adequate manner.

5.1.2 Colony parameters

A pattern was detected in the data showing that when the severity of the terrestrial erosion increases, the mean percentage of dead coral tissue of a colony also increases. Considering the percentages, this relationship is close to linear. This relationships may suggest that, on Saba, influx of terrestrial erosion products results in elkhorn tissue death. This corresponds to Van Katwijk et al. (1993), who researched the influence of sediment discharge in the Malindi-Watamu reefs in Kenya and concluded that as a result of this discharge partial mortality of coral tissue occurred and high proportions of injured coral or algae infested coral became present.

However, in this research on Saba, the effect of erosion on colony tissue death was not significant. This can again be the result of small sample sizes which reduces the power to detect an effect, especially for the most severe erosion intensity class where only 13 colonies were measured. In addition, the model including erosion fitted the data better than the nested model without erosion, again indicating an effect of erosion on the parameter. Nevertheless, it should be taken into account that no significance can also refer to no effect of erosion on coral tissue death of a colony.

Even though no direct link between erosion and the elevation of a colony relative to its surrounding was detected, the data showed a decrease in dead colony tissue if the colony is elevated relative to its surrounding when terrestrial erosion is severe, especially when this elevation is more than four meters. A possible explanation for this pattern is that as the turbidity of the water increases, the light availability necessary for photosynthesis decreases. In this case, being elevated is an advantage as more light is available in shallower waters (Te, 1997). In addition, the influence of waves is higher when being shallower. This can help to remove sediment settled on the coral tissue which will prevent coral tissue death (Bak and Elgershuizen, 1976). It should be noted that the estimates in the fitted model are not significant. However, the model that includes the interaction between erosion and relative position fits better to the data than the model without this interaction. This information suggests that a link is present and emphasized the importance of further research of this relationship.

A significant difference in colony depth is present between erosion intensity class 2 (extremely high) and one or both of the other erosion intensity classes. The measured colonies of erosion intensity class two are located at deeper depths than the colonies of the other classes. It is suggested that further research is conducted on this parameter to find an explanation for this phenomenon.

Furthermore, at the most severe erosion intensity class colonies are more often located on a dead colony than at the other lower erosion intensity classes. A possible explanation could be that a combination of processes is present at sampling sites with the most severe erosion intensity class. First of all it might be possible that only limited suitable sampling sites are present for colonies to grow as the negative consequences of sediment in the water, such as turbidity, are high. Secondly, at the same time mass mortalities occur after heavy rainfall events, when high influxes of sediment enter the ecosystem. Consequently, dead colonies are present on the few suitable settle sampling sites and as a result new colonies settle on the old dead ones. However, it should be noted that more factors, that are not included in this research, are influential for the settlement sampling sites of the colonies. In addition it should be taken into account that the difference in substrate is possibly a coincidence since the sample sizes are small (table 7).

Moreover, it could be concluded that water temperature on Saba is not a determining factor for elkhorn occurrence as the temperatures where elkhorn was absent were the same as where elkhorn was present. However, this does not directly indicate that patters detected are a direct consequence of erosion. As discussed before, many factors are present in the ecosystem that can have an influence on site conditions of elkhorn which might not be included in this research.

No effect of erosion on the colony cover of sediment was found. This is against the expectation that severe terrestrial erosion will result in more cover of sediment. Rogers (1983) proposed that elkhorn is specifically vulnerable to sedimentation as particles can accumulate on the flat surface of the coral. In addition he concluded that this species is very ineffective in the removal of sediment, which also corresponds to findings of Bak and Elgerhuizen (1976). Furthermore, Rogers states that elkhorn mostly relies on wave action for the removal of sediment. One of the findings of this research on Saba that corresponds to Rogers' findings is that wave action has a strong interaction with elkhorn occurrence, as no elkhorn was present at the sampling sites without wave action. In addition, no sediment was discovered on alive colony tissue, which also provides support for Rogers' theory that wave action is essential for sediment removal. However, when no sampling sites with elkhorn and without wave action are present, it is not possibility to test this theory. Furthermore, the fact that no sediment was discovered on alive tissue questions Rogers' suggestion that elkhorn is a very ineffective sediment remover.

Moreover, no effect of erosion was observed on the average angle of the most dominant slope the colony has with its substrate. In addition, no effect was observed of erosion on the mean cross section of palmata colonies. This contradicts the findings of Cortés and Risk (1985), who concluded that sedimentation at two sites in Costa Rica resulted in a larger average colony diameter of three coral species measured.

However, a significant relation between the angle of the most dominant slope and the cross section was detected. When the angle of the most dominant slope increases, the largest cross section decreases. An explanation can be that increasing branch weight becomes more obstructive for colonies on a steep slope and as a result the branches break. In addition, when colony depth increases to a maximum of six meters, the angle of the most dominant slope decreases. It is expected that a large slope angle will prevent sediment to settle on the coral tissue. Further research in these two relations is suggested to find an explanation and possibly a link to erosion severity.

5.2 Research limitations and recommendations

5.2.1 Potential erosion intensity map

The potential erosion intensity map created during the predictive phase of the research is believed to provide an indication of sufficient quality for this research. However, on site assessment proved that predictions on severity of erosion on a small scale are difficult, as not every sampling site was classified in the right erosion intensity class. Addition of extra parameters can improve the potential erosion intensity map, especially the predictions for coastal areas. For example, a parameter for the dominant wind direction could be included in the map. The waves resulting from this wind can have an influence on the abrasion of the coast.

Furthermore, in the resulting potential erosion intensity map it can be noticed that on the south-west side of the island a 'No Data' area is present. This is a result of data missing for that area in the land use dataset, probably as a consequence of a cloud present in the aerial photographs used to create the land use dataset. For further research it is recommended to create a land use map in which data is present for the whole island. This map can then be included in the process of creating the potential erosion intensity map.

Moreover, the potential erosion intensity map would be more useful for determining levels of sediment influx if the length of the slope laying behind the area is also included, as influx of sediment strongly depends on erosion upstream or on top of the hill. In addition, the position of the natural and artificial drainage channels can be included as the runoff at the end of these channels is expected to be high after rainfall events. Furthermore, the use of more precise soil data can strongly improve the quality of the potential erosion intensity map. The soil map used in this research was very undetailed resulting in less accurate predictions of the erosion intensity. Finally, if the level of erosion severity was not given in classes, but as a numeric value, other data analysis techniques, such as regression, could be used to determine the effect of erosion on the different parameters.

5.2.2 Data collection

Due to time limitations, dives could be made at only five or six sampling sites per erosion intensity class. The addition of more sampling sites could strongly improve the quality of the findings of the research. An increase in the number of sampling sites allows for conduction of more valid statistical tests on the data.

Furthermore, the quality of the results could be improved when extra habitat and colony parameters are added which are measured at the different sampling sites. Habitat conditions and colony characteristics are dependent on many more factors that were not included in this research (e.g. predators and level of anthropogenic interference). It would be interesting to include GPS sampling sites of the colonies, ideally measured underwater during the dive, to examine the distance of a measured colony to the coast. This allows for assessment if the influence of sediment influx becomes less farther from the coast. Unfortunately the right equipment was not available for this research.

Moreover, in this research the transparency was assessed as a proxy for turbidity with the use of a secchi disk. However at most of the sampling sites the vertical transparency was to the bottom. This made it difficult or even impossible to adequately compare the transparency at different sampling sites. For further research it is strongly recommended to use a less visible secchi disc or the horizontal visibility as a measure for turbidity. The horizontal visibility can be measured using measuring tape and two divers. One diver holds on to a secchi disc which is connected to the measuring tape and hold the disc in such a way that the top of the disc is in the direction of the second diver. The second diver holds on to the measuring tape and swims away from the first diver. The second diver checks at which distance from the first diver the secchi disc is not visible anymore. This is then the horizontal visibility. Even though this horizontal visibility was not officially measured for this research, it was observed that at most sampling sites the visibility was good, in most cases estimated at 20 plus meters. However, it should be noted that transparency is not constant and varies over time. Severe differences in transparency can be present after heavy rainfall events when the water flushes great amounts of loose sediments into the water. The secchi disk measurements were done only once at each sampling site. Measuring the turbidity several times on the same sampling site will strongly improve the accuracy of the parameter. It might also be interesting to split the transparency in two separate parameters; the first being the transparency at normal weather conditions, and the second the transparency straight after a heavy rainfall event.

Transparency is not the only parameter that can change strongly over time. Presence of a current can also vary at the same sampling site. Therefore, it is also recommended for further research or in other comparable researches to come back to the same sampling site a couple of times to determine the presence or absence of a current.

Furthermore, in this research the parameter 'Cover of sediment' provided an indication if sediment was present on the alive coral tissue. It turned out that that at none of the 78 colonies this was the case. However, it was observed that if part of the colony was dead, in some cases sediment was present on that tissue. In further research or comparable research it would be interesting to add an extra parameter which also assesses sediment present on the dead part of the coral tissue and that quantifies the thickness of this sediment or the thickness of the algae layer present in which the sediment accumulates. This information would be useful for determining the impact of sedimentation and predicting the death causes of dead coral tissue.

Moreover, the parameter 'Slope angle', which gives the angle of the most dominant slope the colony has with the substrate, should be altered in a parameter measuring the angles of the flat branches of the colony tissue itself. In this way it can be assessed if the morphology of elkhorn colonies present at a high erosion intensity class differs from the morphology at a lower erosion intensity class. In theory a steep slope of the flat branch can prevent sediment to settle on the colony and it is therefore interesting to examine if steeper slopes are present when the severity of erosion increases. However, it should be noted that a negative effect of a steep slope can be that it is more difficult for the branch to catch light.

Finally, for further research it is recommended to ensure a more objective method of data collection. Some of the parameters used in this research are estimated by the diver, such as the percentage of colonies that is dead in a habitat. Even though these parameters were estimated by two divers individually, the results are subjective. Quantification of these parameters can improve the quality of the results. In example, when there is more time available to conduct the research, at each sampling site an area with the same size can be used in which all the colonies are counted and the true percentage of the colonies that are dead in this area can be calculated.

5.2.3 Data analysis

Even though patterns in the data that indicated an effect of erosion are present, these effects were often not significant. It is presumed that when more sampling sites and more colonies are added to the data, some of these effects will be significant. As a result the biggest limitation to this research is the small sample sizes as they decreased the power of statistical test to detect a significant difference. In addition, when the sample sizes increase, other statistical analyses could be conducted with the data. In example, regression and classification trees could be used. This methods enables to explain variation of a single response variable and makes it possible to assess to what extent the measured parameters are linked to the severity level of erosion and, most importantly, it can tell which parameters are the most determining for observed effects (De'ath & Fabricius, 2000).

Furthermore, some comments on the methods of data analysis in this research should be made. Firstly, in order to predict the effect of erosion on the probability of elkhorn occurrence and on the total dead colonies in a habitat, regression is used. Theoretically this method is not suitable for the data as the erosion intensity class is a factor from which it is not certain if the difference in severity between the different classes equal. Therefore, if the erosion intensity class was numeric, as suggested before, the results of the regression will be of a higher quality and more reliable.

In addition it should be noted that the predicted confidence interval of the percentage of the colonies that is dead in the surrounding at the most severe erosion intensity class, transcends the 100 percent, which is impossible. In order to prevent a predication higher than 100 percent, a different distribution specialised in percentages should be used when fitting the model.

5.2.4 Impacts of the research

The results of this research gain insight in the interconnectivity between terrestrial and marine geo-ecosystems and they accentuate the importance of also considering terrestrial processes in coral reef conservation and management. In addition, the methods and recommendations provided by this research on how to assess the relation between terrestrial erosion and presence and condition of a coral species can be applied by local governments or research institutes for other tropical regions and even other coral species. When applied for other species it should be noted that although most of the parameters proposed will be relevant for all coral species, some parameters may have to be added or adjusted to fit the coral species researched.

The results gained from this research can be used for coastal management and conservation of the fragile coral reef ecosystems. In addition, the findings can be used for two currently ongoing projects on Saba. These projects include the search for suitable sampling sites for the transplantation of coral fragments of *Acropora palmata* and *Acropora cervicornis* and finding sampling sites for building artificial reefs in the Saba National Marine Park.

6. Conclusions

It can be concluded that the probability of elkhorn occurrence decreases on Saba as the severity of terrestrial erosion increases. Furthermore, it is likely that influx of terrestrial erosion products result in an increase of the percentage of dead colonies and an increase in the dead elkhorn colony tissue. Moreover, if a colony is elevated from its surrounding, especially more than four meters, a decrease in dead colony tissue is present when the erosion intensity is extremely high or most extreme. This indicates that the more erosion products enter the coral reef ecosystem, the larger the advantage of being elevated. A possible explanation for this pattern is that as the turbidity of the water increases, the light availability necessary for photosynthesis decreases. In this case, being elevated is an advantage as more light is available in shallower waters. In addition, the higher influence of wave action in shallower water allows for removal of sediment on coral tissue.

However, these three effects of erosion on the parameters were not significant. In addition, erosion is not the only cause that can result in colony death. Diseases, predators and anthropogenic damage are examples of other influential factors that were not included in this research. Nevertheless, it is possible that the lack of significance is a result of the small sample sizes. These have reduced the power to detect a difference between the sampling sites and colonies coupled to the different erosion intensity classes.

A significant difference in colony depth is present between erosion intensity class 2 (extremely high) and one or both of the other erosion intensity classes. Colonies at erosion intensity class 2 are located deeper than the other colonies. No effect of terrestrial erosion was detected on the abundance, cover of sediment, cross section and the average angle of the most dominant slope. Furthermore, temperature, and current were not determining factors for the presence of elkhorn on Saba. It is concluded that the presence of wave action is very important for elkhorn occurrence. However, wave action did not explain all the elkhorn occurrences.

Furthermore, significant relations were detected between the angle of the most dominant slope and the cross section and colony depth. Further research in these two relations is suggested to find an explanation and possibly a link to erosion severity.

In order to improve the quality of the results of this research, bigger sample sizes are necessary. For future research it is highly recommended to increase the amount of habitat and colony observations. This will enhance the power of statistical test to detect significant effects. In addition, it is advised to change the erosion intensity into a numeric variable instead of a factor. This will allow for adequate use of other suitable statistical techniques such as LM regression. Furthermore, it is strongly advised for further research to use horizontal visibility rather than vertical transparency as proxy for water turbidity.

The results of this research gain insight in the interconnectivity between terrestrial processes and marine ecosystems. In addition, they emphasize the importance of considering both marine and terrestrial processes in conservation and management of coral reefs. Furthermore, the workflow developed, and the recommendations provided by this research can be applied by research institutes or local governments to assess the effect of terrestrial erosion on coral species in other tropical regions.

7. References

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Author

Amber Mulder

9. Appendix

A – Methods for creating the potential erosion intensity map

The potential erosion intensity map visualises the assumed erosion risk of terrestrial Saba by combining basic parameters of soil erosion. The map is created using the ArcMap 10.4.1 software and the methods are based on the PAP and FAO guidelines for mapping rainfall-induced erosion processes in the Mediterranean coastal areas (PAP & FAO, 1997). Raster calculations with specific matrixes adapted to the local environment are used to integrate erodibility and soil protection scores to form erosion intensity scores. For all the maps created the coordinate system WGS 1984 UTM Zone 20N is used.

The erodibility scores are calculated by combining preliminary data of slope and soil types (figure 17). Slope data is created with the use of a DEM (Digital Elevation Model) from the SCF (n.d.(a)). With the help of the spatial analyst tool 'slope', a raster is created showing the slope percentages of Saba island (figure 18). Two extra classes are added to the proposed five classes of PAP and FAO, as the slopes on Saba are extremely steep that without addition of two classes 82 percent of the whole island would fall within the highest slope class (Extreme (>35%). The extra classes are created by dividing the highest slope class of the PAP and FAO guidelines into three groups (table 8).

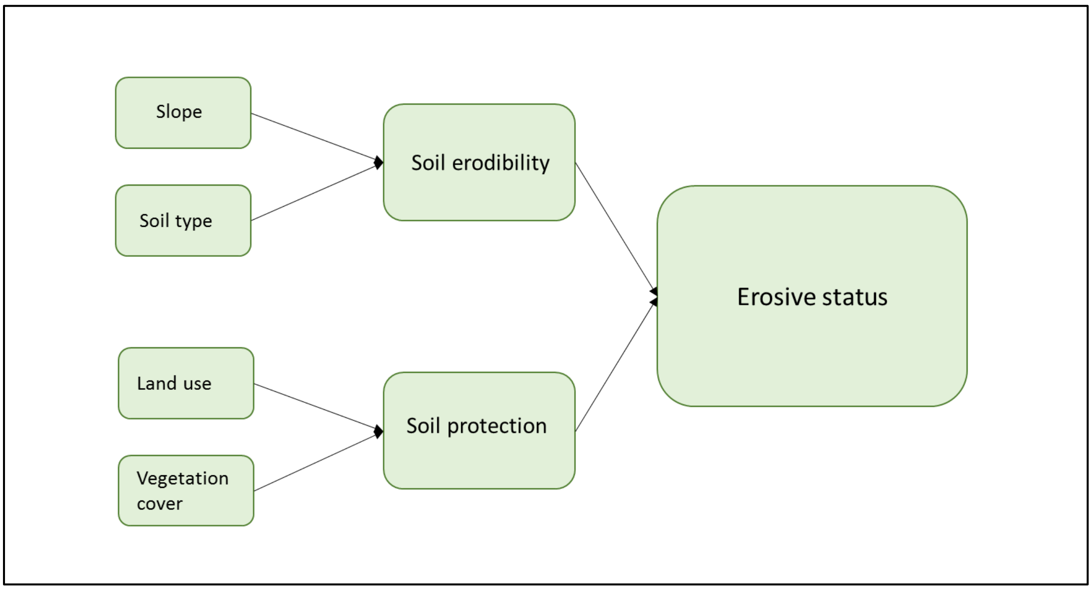

Figure 17: Simplified overview of the creation process of the potential erosion intensity map

Table 8: Slope classification

Slope class	Description
1	Flat to gentle (0-3%)
2	Moderate (3-12%)
3	Steep (12-20%)
4	Very Steep (20-35%)
5	Extreme (35-100%)
6	Very Extreme (100-165%)
7	Most Extreme (165-1.000%)

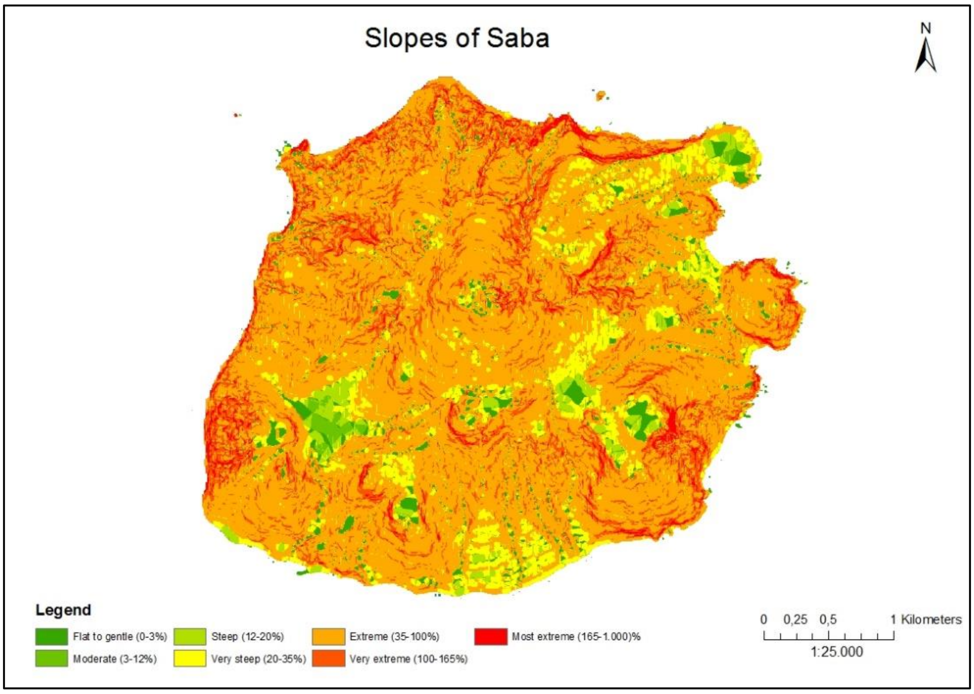

Figure 18: Slope map of Saba island (Source: SCF (n.d.(a)). Adapted by A.E. Mulder)

The soil type map is created with the use of data from Koomen, Van Dorland and Makaske (2012). The different soils are classified based on their soil texture. The higher the class, the coarser the texture (table 9 & 10 and figure 19).

Table 9: Soil classes on Saba

Soil class	Soil type
1	Clay loam
2	Sandy loam
3	Stony loam
4	Stone

Table 10: Classification of the soils of Saba

Abbreviation	Name	Soil Class
Rs	Very steep stony land	4
Gi	Gille's cherty sandy loam	2
Mi	Middle island very stony loam	3
Bt	The Bottem sandy loam	2
Bo	Booby Hill very stony loam	3
Jo	St. John's sandy loam	2
Re	Rendez vouz stony loam	3
Sc	Scenery clay loam	1

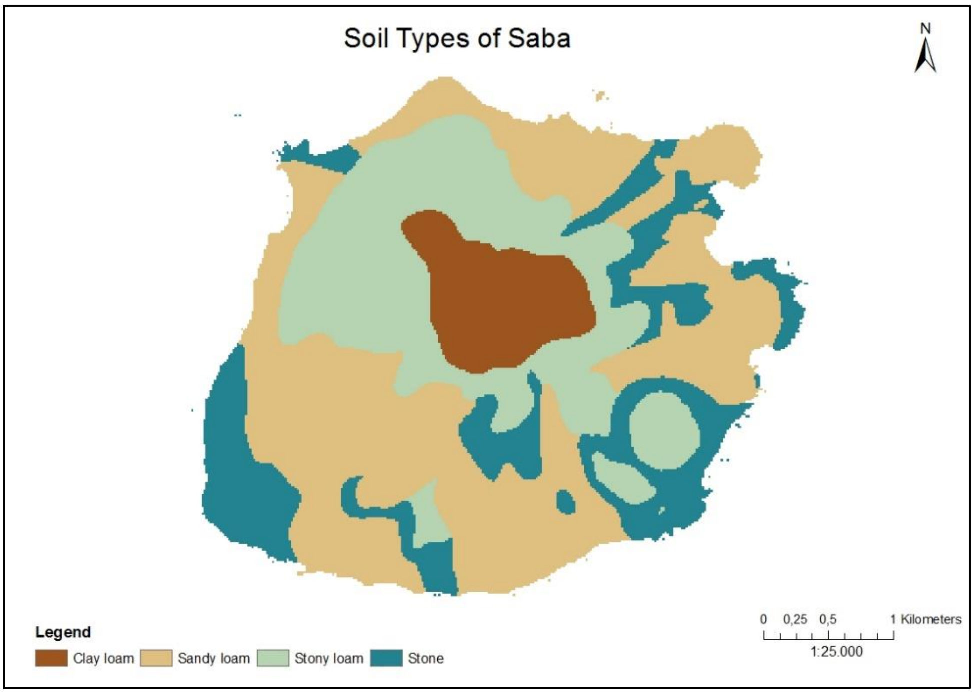

Figure 19: Soil type map of Saba (Source: Koomen, Van Dorland & Makaske (2012). Adapted by A.E. Mulder)

Hereafter the raster calculator and the reclassify tool are used to apply a matrix for soil erodibility that combines the created slope raster and the soil raster (table 11 & 12). The higher the class, the higher the soil erodibility. The perception is followed that, in general, the steeper the slope, the more vulnerable the soil is to erosion. Furthermore, soils rich in loam and fine sand are the most vulnerable to erosion and non-weathered compact rock the least. These assumptions are based on the conducted literature study presented in the theoretical framework. However, the soil erodibility class assigned to an area depends on the specific combination of both the slope and the soil type. When a slope is steep, weight of lose material will probably have more influence on if the material is dislodged than its ability to dissolve or to be lifted by wind. The opposite is the case for areas with flat or gentle slopes. The resulting soil erodibility map is given in figure 20.

Table 11: The matrix applied to create the soil erodibility raster

Soil type> *Slope class˅*	**1 Clay loam**	**2 Sandy loam**	**3 Stony loam**	**4 Stone**
1	1	1	1	1
2	2	3	2	1
3	3	4	3	2
4	4	5	4	4
5	5	6	5	5
6	6	7	6	6
7	7	7	7	7

Table 12: Classification of soil erodibility

Level of erodibility	**Description**
1	Low
2	Moderate
3	Medium
4	High
5	Extreme
6	Very Extreme
7	Most Extreme

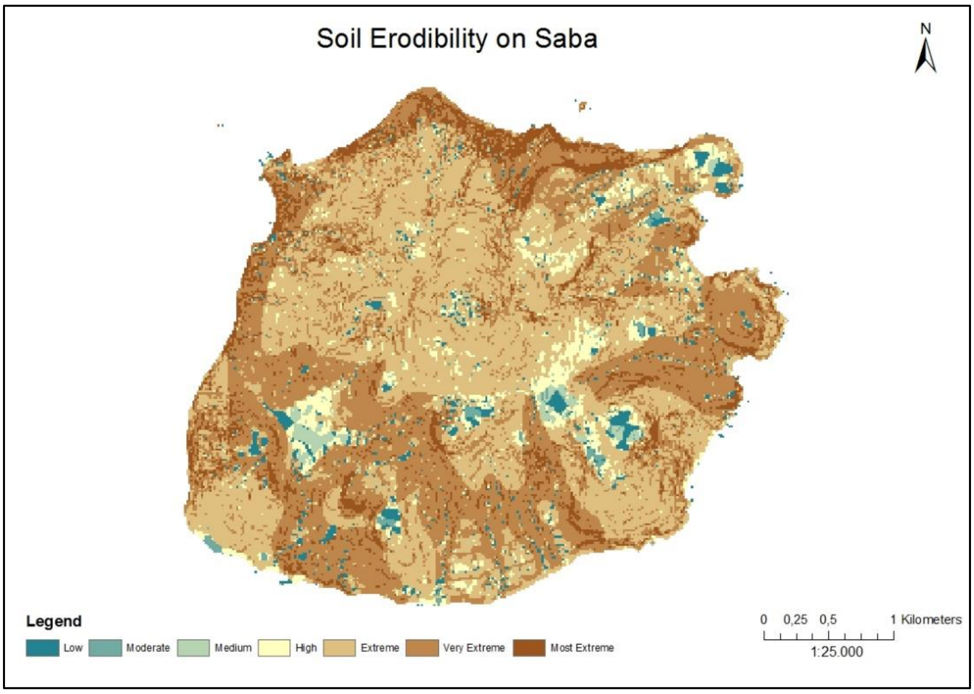

Figure 20: Soil erodibility map of Saba (Created by A.E. Mulder)

Next the soil protection scores are calculated by using a combination of vegetation cover data from DCBD (2014) and land use data from Smith, Mücher and Debrot (2014). The vegetation data of DCBD gives the dominant vegetation species in polygons. For each different species it is checked what type of vegetation it is, for instance grass, and it is linked to a vegetation cover percentage based on the vegetation cover percentages of PAP and FAO (1997) (table 13 & 14 and figure 21). The data also includes urbanized areas and the airport. Both these types are classified as more than 75% cover as it is assumed that the buildings places on the soil protect it from erosion as it is kept together.

Table 13: Vegetation cover of the vegetation on Saba

Type	Percent cover
Aristida Cliffs	<25%
Bothriochloa Mountains	<25%
Aristida-Bothriochloa Mountains	<25%
Coccoloba-Inga Mountains	25%-50%
Swietenia Mountains	50%-75%
Philodendron-Inga Mountains(Mm2)	50%-75%
Coccoloba-Wedelia Mountains(Mm4)	50%-75%
Cyathea-Charianthus Mountains	>75%
Philodendron-Marcgravia Mountains	>75%
Philodendron-Inga Mountains (Mg3)	>75%
Philodendron-Inga Mountains (Mmg7)	>75%
Urbanized areas	>75%
Airport	>75%

Table 14: Classification of vegetation cover

Class	Vegetation cover
1	Less than 25%
2	25%-50%
3	50%-75%
4	More than 75%

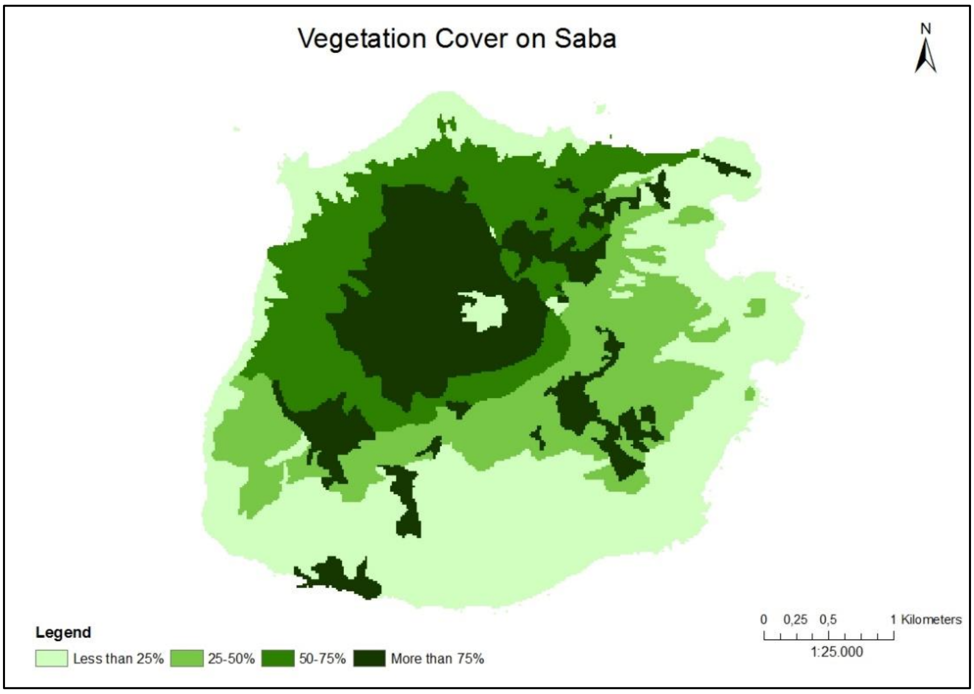

Figure 21: Vegetation cover map of Saba (Source: DCBD (2014). Adapted by A.E. Mulder)

The land use data comprises 17 different types of land use on Saba. These types are reclassified in 6 classes and one 'no data' class. The classes are based on the land use classes of PAP and FAO (1997) and are expected to have a different influence on soil erosion. The PAP and FAO guidelines could not be followed completely as they have a strong focus on agriculture, which is very uncommon on Saba (De Freitas et al., 2016). The classification is therefore adjusted to the local environment. The higher the score, the more the land use type is assumed to stimulate erosion (table 15 and figure 22).

Table 15: Classification of the land use on Saba

Class	Description
0	-No Data
1	-Informal Housing -Roads and trail networks and associate land -Airport -Sea
2	-Forest broadleaved evergreen -Forest dry broadleaved evergreen
3	-Forest deciduous seasonal
4	-Thorn shrub
5	-Invasive Corallita -Invasive Elephant grass -Pastures -Herbaceous rangeland
6	-Rubble -Bare rocks -Mine, dump and construction sites

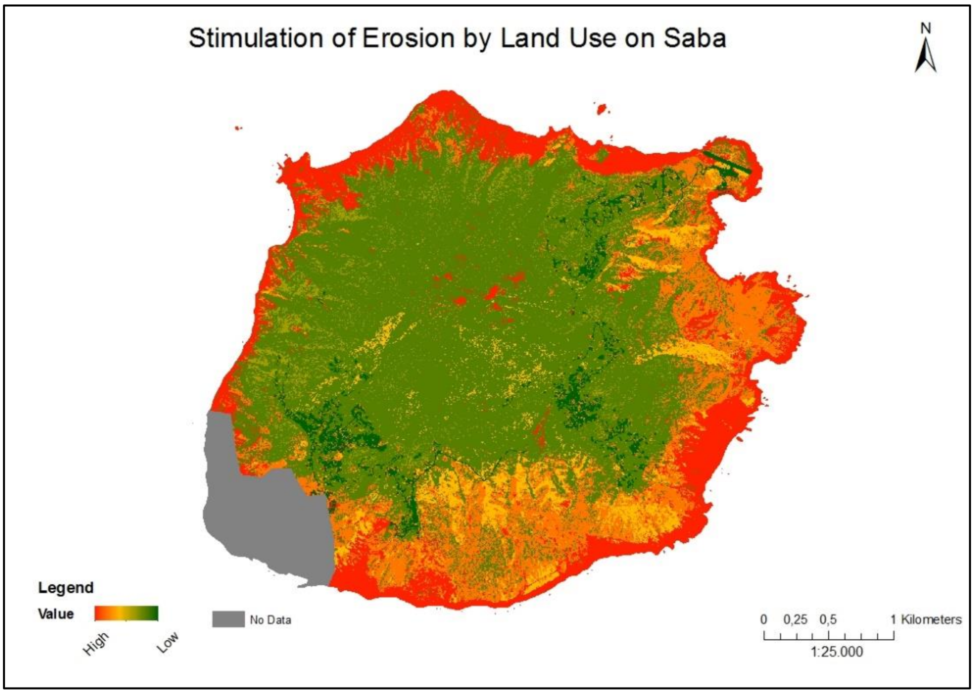

Figure 22: Map indicating the severity of the stimulating effect that the land use type has on erosion (Source: Smith, Mücher and Debrot (2014). Adapted by A.E. Mulder)

Hereafter, the raster calculator and the reclassify tool are used to apply a matrix for soil protection which combines the created vegetation raster and the land use raster (table 16 & 17). This matrix is based on the land use versus vegetation cover matrix of the PAP and FAO (1997), and follows the general assumption that the higher the vegetation cover, the less vulnerable the soil is to erosion. The resulting soil protection map is given in figure 23. The higher the class, the lower the soil protection against erosion.

Table 16: Matrix applied to create the soil protection map

Vegetation cover > *Land use^V*	**1**	**2**	**3**	**4**
1	1	1	1	1
2	3	2	1	1
3	4	3	2	2
4	5	4	3	2
5	5	4	3	3
6	5	5	4	3

Table 17: Classification of the soil protection map

Level of soil protection	**Description**
1	Very high
2	High
3	Medium
4	Low
5	Very low

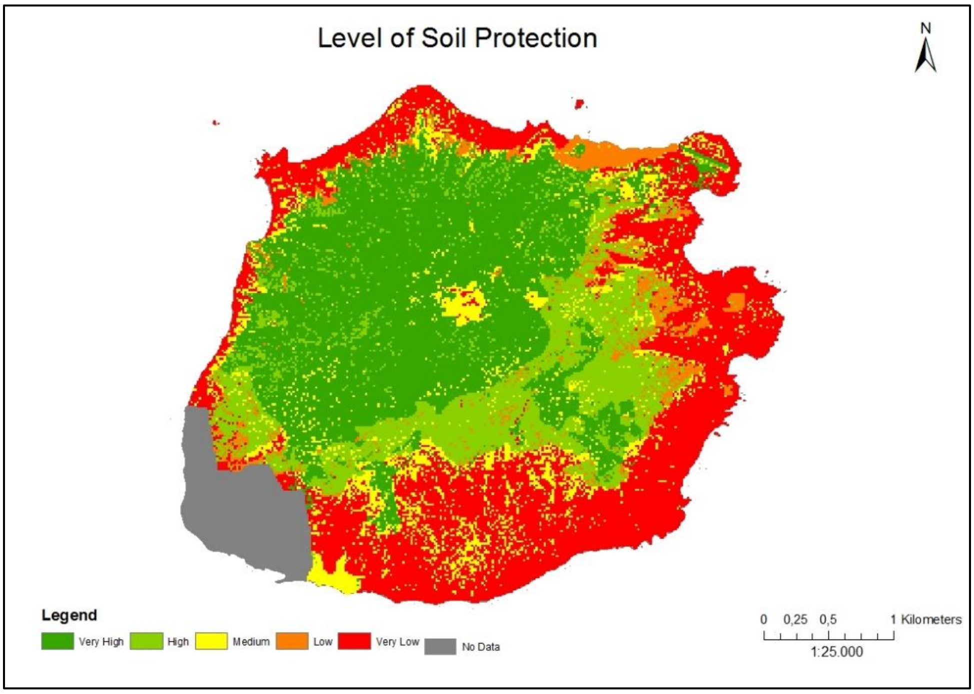

Figure 23: The level of soil protection map of Saba (Created by A.E. Mulder)

In the last step for creating the potential erosion intensity map the raster calculator and the reclassify tool are used to combine soil erodibility with soil protection. A matrix is applied in which 7 classes of erosion intensity are defined (table 18 & 19). This is two more than the guidelines of PAP and FAO propose, however, the addition of two classes was done since the use of five classes resulted to be insufficient. For this research the differences in erosion intensity of the coastal areas is relevant and with five classes the whole coast was classified in the same, most extreme, erosion intensity class. Adding two extra classes made it possible to make clear distinctions between the erosion intensity of different coastal areas. The higher the erosion intensity level at the coast, the more sediment is expected to enter the ocean. The resulting map is given below in figure 24. It can be noted that on the south-west side of the island a 'No Data' area is present. This is a result of data missing for that area in the land use dataset. It is predicted that this is a consequence of a cloud present in the aerial photographs used to create the land use dataset.

Table 18: The erosion intensity matrix. Erodibility ranges from low (1) to most extreme (7) and soil protection ranges from very high (1) to very low (5).

Erodibility> *Soil protection˅*	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1	1	1	1	2	2	3	3
2	1	1	2	3	3	4	4
3	1	2	3	4	4	5	6
4	2	3	3	4	5	6	7
5	2	3	4	5	6	7	7

Table 19: Classification description for erosion intensity

Erosion intensity level	Description
1	Very low
2	Low
3	Appreciable
4	High
5	Very high
6	Extremely high
7	Most Extreme

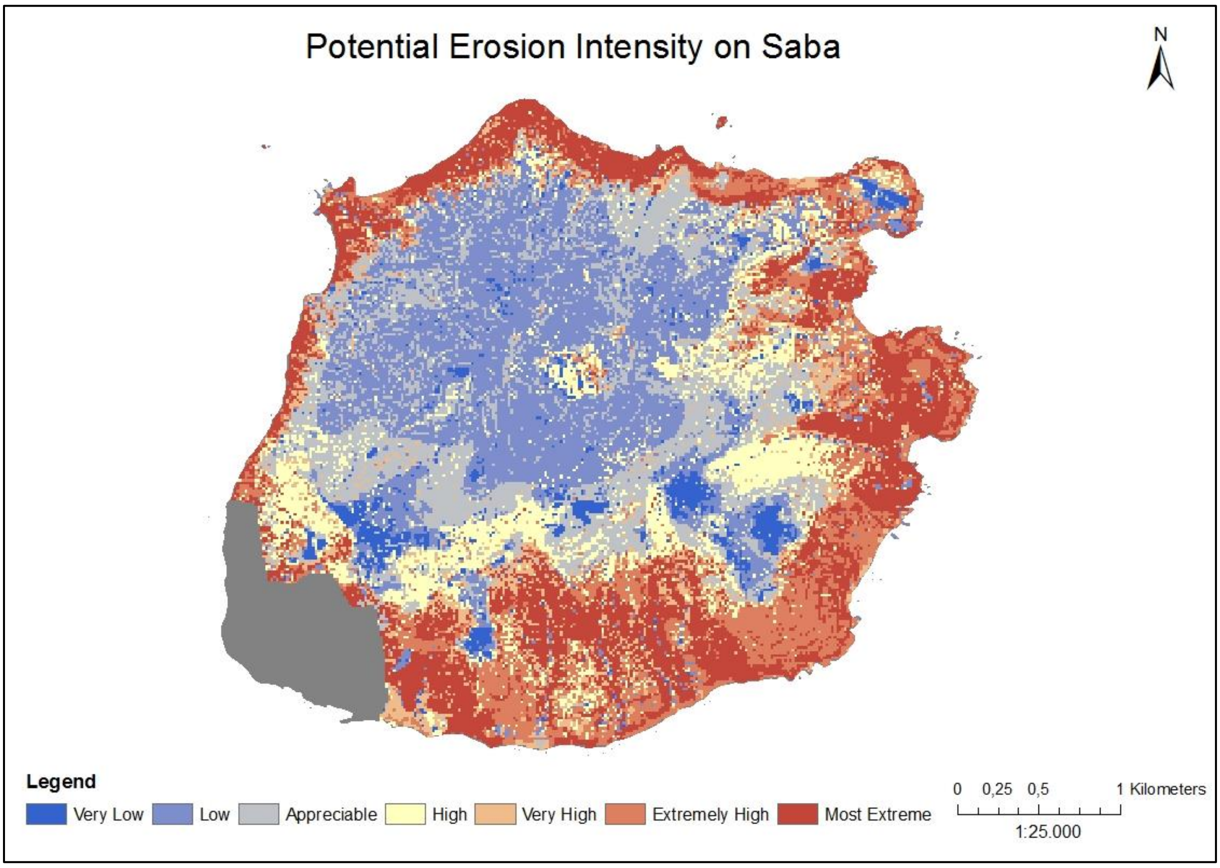

Figure 24: Potential erosion intensity map of Saba created by the integration of the level of erodibility map and the level of soil protection map (created by A.E. Mulder)

B – Table of the fitted GLM's and LM's and ANOVA's

Table 20: Results of the models fitted and the ANOVA tests performed to examine the influence of erosion on the parameters and relations between parameters. ES1= Erosion intensity 'very high', ES2= Erosion intensity 'extremely high', ES3= Erosion intensity 'most extreme'. The p-values are the results of two-sided test with exception of the 1ST(one-sided test) p-values.

Parameters	Function	Type	Coefficients	P-value
Elkhorn present & Erosion intensity	*Elkhorn present ~ Erosion intensity-1*	GLM, ANOVA, binomial distribution	ES1= 19.57 ES2= 0.69 ES3= -0.41	ES1=0.997 ES2=0.423 ES3=0.657
	Elkhorn present ~Erosion intensity & Elkhorn present ~ 1	ANOVA, binomial distribution. Comparing two GLM, ANOVA models with binomial distribution	-	0.064 1ST =0.032
	Elkhorn present ~ Erosion intensity	GLM regression, logit transformation, binomial distribution	Intercept: 4.64 Slope: -1.76	0.069 1ST=0.034
Total dead surrounding & Erosion intensity	*Total dead surrounding ~ Erosion intensity - 1*	LM, ANOVA, log transformation, gaussian distribution	ES1= 4.19 ES2= 4.28 ES3= 4.44	ES1=1.35E-10 ES2=2.76E-10 ES3=3.24E-09
	Total dead surrounding ~ Erosion intensity & Total dead surrounding ~ 1	ANOVA, gaussian distribution. Comparing two LM log transformed ANOVA models with gaussian distribution.	-	0.45 1ST=0.23
	Total dead surrounding ~ Erosion intensity	LM regression, log transformation, gaussian distribution	Intercept: 4.06 Slope: 0.12	0.20 1ST=0.1
Dead coral tissue & Erosion intensity	*Dead coral tissue ~ Erosion intensity & Dead coral tissue ~ 1*	ANOVA, gaussian distribution. Comparing two LM ANOVA models with gaussian distribution.	-	0.26 1ST=0.23
Dead coral tissue, Relative position/ elevation & Erosion intensity	*Dead coral tissue ~ Erosion intensity * Elevation*	LM ANOVA, gaussian distribution	ES1= 10.69 ES2= 7.88 ES3= 13.48 ES1+Elevation= 2.31 ES2+Elevation= -17.55 ES3+Elevation= -26.48	ES1= 0.012 ES2= 0.18 ES3= 0.081 ES1+Elevation= 0.83 ES2+Elevation= 0.31 ES3+Elevation= 0.30
	Dead coral tissue ~ Erosion intensity + Relative position + Erosion intensity: Relative position & Dead coral tissue ~ Erosion intensity + Relative position	ANOVA, gaussian distribution. Comparing two LM ANOVA models with gaussian distribution.	-	0.31
Angle of slope & Erosion intensity	*Angle of slope ~ Erosion intensity & Angle of slope ~ 1*	ANOVA, gaussian distribution. Comparing two LM ANOVA models with gaussian distribution.	-	0.48
Cross section largest &	*Cross section largest ~ Erosion intensity &*	ANOVA, gaussian distribution. Comparing	-	0.78

Erosion intensity	*Cross section largest ~ 1*	two LM ANOVA models with gaussian distribution.		
Colony depth & Erosion intensity	*Colony depth ~ Erosion intensity*	LM ANOVA with gaussian distribution	ES1= 5.39 ES2= 1.66 ES3= -0.65	ES1= 2E-16 ES2= 0.00049 ES3= 0.28
	Colony depth ~ Erosion intensity & *Colony depth ~ 1*	ANOVA, gaussian distribution. Comparing two LM ANOVA models with gaussian distribution.	-	0.00014
Colony depth & Angle of slope	*Angle of slope ~ Colony depth* & Angle of slope ~ 1	ANOVA, gaussian distribution. Comparing two LM regression models with gaussian distribution.	-	0.00087
Cross section largest & Angle of slope	*Cross section largest ~ Angle of slope* & *Cross section largest ~ 1*	ANOVA, gaussian distribution. Comparing two LM regression models with gaussian distribution.	-	0.0026

C – Result plots

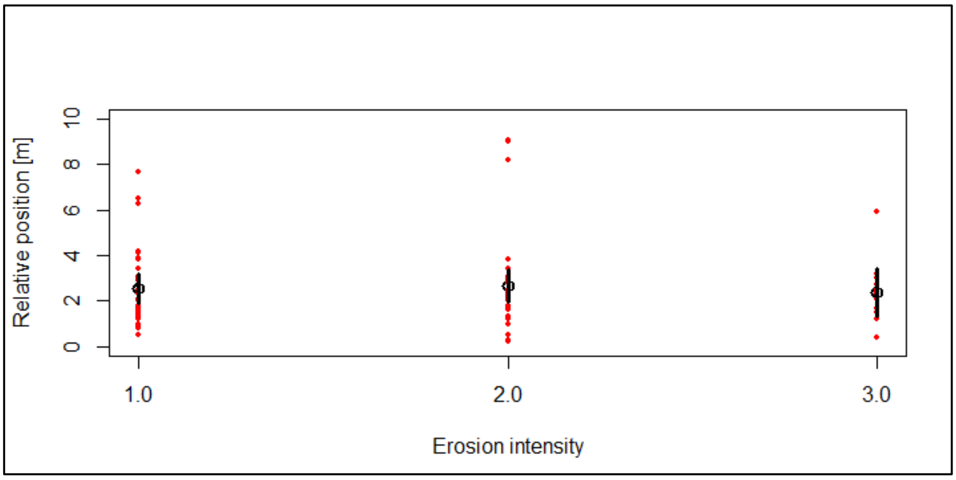

Figure 25: The mean elevation of the colonies relative to its surrounding at different erosion intensity classes including its 95% confidence interval. Erosion intensity 1= very high, erosion intensity 2= extremely high, erosion intensity 3=most extreme. The data points are given as red dots (n=78).

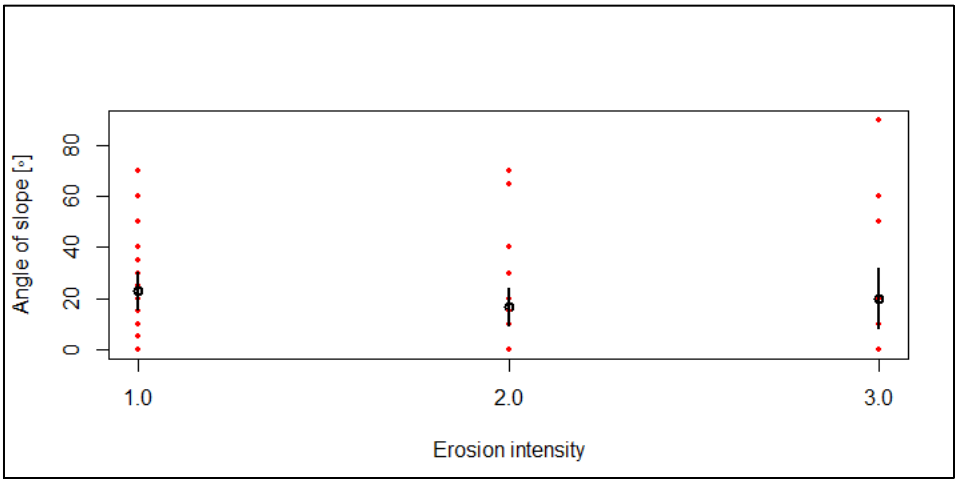

Figure 26: The mean angle of de most dominant slope that colonies make with its substrate at different erosion intensity classes. The 95% confidence interval is included. Erosion intensity 1= very high, erosion intensity 2= extremely high, erosion intensity 3=most extreme. The data points are given as red dots (n=78).

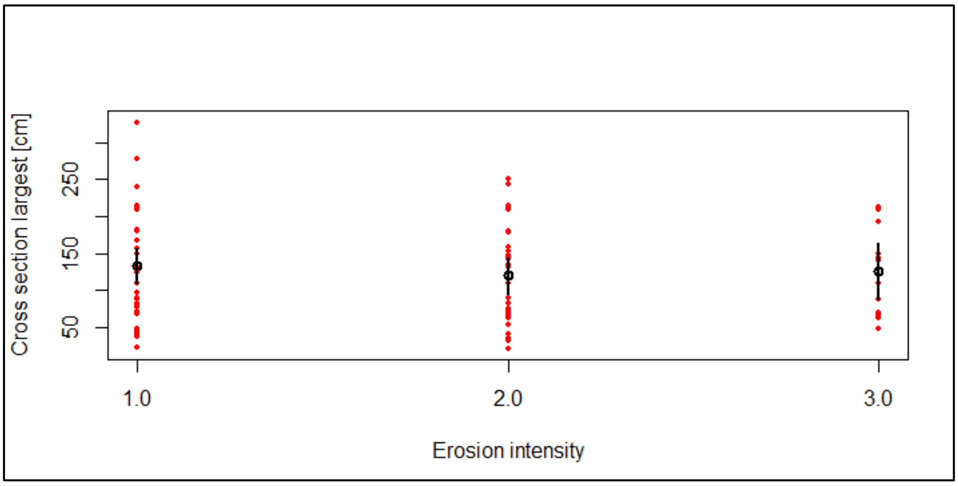

Figure 27: The mean largest cross section of the colonies at different erosion intensity classes. The 95% confidence interval is included. Erosion intensity 1= very high, erosion intensity 2= extremely high, erosion intensity 3=most extreme. The data points are given as red dots (n=78).