MODELING REEF HEALTH FROM UPSTREAM SOCIO-ECOLOGICAL COMPONENTS USING GIS AND RS

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ABSTRACT

Ecological services provided by coral reefs are threatened by complex dynamics of global and local drivers. Fostering an appropriate management at local scale may enhance the resilience of the coral reefs facing large-scale issues, more laboriously manageable. We propose to model a bespoke reef health index (RHI) using a comprehensive dataset of socio-ecological variables and the Boosted Regression Trees (BRT). The variation of the RHI was primarily explained by the cluster of physiographic variables (55.45%), to a lesser extent, by land cover (36.42%), and finally by sociological variables (8.12%). The dispersion and the mean of the slope, as well as the built-up area increasingly contributed to the satisfactory modeling of the RHI (14.07, 14.12, 15.37%, respectively). These results will hopefully be useful for the stakeholders tasking with integrated coastal sustainability.

Index Terms— Non-linear modeling, terrestrial runoff, landscape monitoring, Pacific Islands.

1. INTRODUCTION

The livelihood of 500 million people worldwide is intricately linked with the ecological services provided by coral reefs and nested ecosystems, such as seagrass beds and mangrove forests [1]. However these crucial ecosystems have been dramatically degraded over the last decades owing to the proximal (e.g. overfishing [2] and sedimentation [3]) and distal anthropogenic activities (e.g. ocean acidification and warming [4]). Unlike distal forcing factors occurring at large-scale, the influence of proximal factors can be more easily embraced and altered by an adequate management at local-scale, thus reinforcing the coral reef resilience hedging against larger-scaled uncertainty and surprise [5]. Obviously interacting with the coral reef structure, the upstream-located anthropogenic influence has to be taken into account when searching for a robust model predicting the coral reef health. In this study, we propose to reliably model the reef health index (RHI, deemed as a good proxy of the sustainability of coral reef processes) of the fringing reef on Moorea (French Polynesia) as a function of the socio-ecological components. Focusing on the watershed-scale sphere of influence, we carried out a non-linear modeling of the reef health index using explanatory sociological and ecological variables derived from GIS (2007 population census) and RS (2006 QuickBird-2 imagery).

2. METHODOLOGY

2.1. Study site

Moorea is a small (c.a. 135 km²) and relatively young (between 1.15 and 2.45 My old) tropical high volcanic island with a rugged topography. It is divided into 57 watersheds separated by knife-edges ridges and high peaks, reaching 1,207 m (Mont Tohiea). Located at only 18 km to the “capital island” of Tahiti (17°28’36’’S, 149°48’18’’W), the largest (1,045 km²) and most populated island of French Polynesia (178,000 inhabitants in 2007), Moorea is experiencing a recent rapid demographic growth, with a population increase of 35.5% between 1996 and 2007 [6] to a current population of ca. 17,000 inhabitants (density of 126 per km²). Rapid growth has led to increasing anthropogenic impacts, such as urbanization, land conversion, plant invasions and fires. Hosting a substantial amount of lagoon fishermen, Moorea exhibits a typical coral reef structure of a volcanic island in the South Pacific, namely fringing reef, channel, barrier reef, reef crest and outer reef. Insofar as the lagoon currents have the potential to geographically deviate the influence of the landward factors and as they reach their highest velocity nearby the main lagoon channel, we investigated the live coral cover of the fringing reef assuming that this reef area was tightly related to its associated watershed. The 57 watersheds were delineated over a 5 m Digital Elevation Model (DEM) but two of them (corresponding to the Opunohu valley) were not considered further in the analyses since they have no fringing reef. For the 55 remaining watersheds, the sphere of influence towards the fringing reef was thoroughly extended from the watershed boundary to the channel.

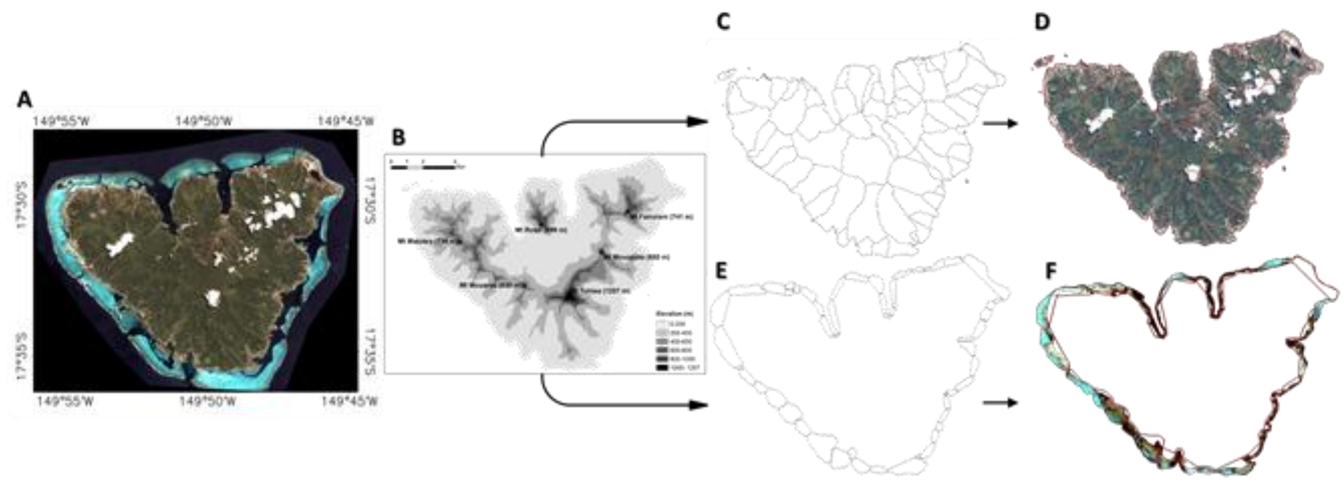

Figure 1: Workflow used for describing the reef health state and the upstream landscape components from a Quickbird-2 image of the island of Moorea. A: The true color composite of the Quickbird-2 image; B: The DEM; C: Delineation of the watersheds; D: Land cover components are derived from the satellite imagery for each watershed; E: Delineation of the sphere of influence of each watershed; F: A reef health index is calculated from the satellite imagery for each sphere of influence.

2.2. The live coral cover

Within the watershed-extended fringing area, the Reef Health Index (RHI) was quantified from the results of a supervised classification applied to a QuickBird-2 (QB2) imagery (Figure 1).
The satellite dataset was acquired on 6 November 2006 with the QB2 sensor, leveraging a four-band (blue, green, red and infrared) multispectral set at 2.4 m resolution and a 0.6 m panchromatic band. Even though our image provider carried out pre-processing image including orthorectification, radiometric correction and pansharpening yielding a four-band dataset at 0.6 m, we resampled the dataset at 5 m to match the watershed resolution.
Prior implementing the RHI, the fringing reef was spatially classified into six classes developing a Support Vector Machine (SVM) model trained and validated by 40 and 20 pixels per class, respectively, geographically fitted with a 0.5 x 0.5 m photoquadrat georeferenced with a 0.5 m accuracy Trimble GPS Geo XH. The six classes, selected with their benthic dominance and distribution over the fringing area, include: live coral, dead coral, macroalgae, sand, deep reef and deep water. Insofar as the red band (i.e. the most water-absorbed visible band), centered on 660 nm, can theoretically reach a depth penetration of 2.5 m [7] in clear waters, we considered the first four classes shallower than 2.5 m and the two last ones deeper than 2.5 m.
Once mapped into the six classes, the RHI of each watershed was designed accounting for the relative difference of the live and dead coral cover in the form of a normalized difference ratio:

$$\text{RHI} = (\text{Live}-\text{Dead})/(\text{Live}+\text{Dead}) \qquad (1)$$

Wherein “Live” and “Dead” refer to the state of the coral cover. The RHI tends to 1 when the live coral cover strongly dominates, while decreasing to -1 when the coral cover is fully dead.

2.3. The socio-ecological component

We extracted three types of independent socio-ecological variables for each of the 55 watersheds in order to model their potential effect on the reef health.
Sociological variables were used to describe the socio-economical context of each watershed with an emphasis on human pressure on the landscape/reefscape system for housing, agriculture and fishing. As an outcome of the last census conducted in French Polynesia [6], the *Institut de la Statistique de la Polynésie française* (ISPF) provided us with GIS layers containing discrete values in the range 1-5 relative to the population density, the rate of farmers and the rate of fishermen in the active population.
Physiographic variables were derived from the DEM to quantify the geomorphology of the upstream watershed and encompass the surface area, the windwardness (exposure to trade winds), the mean and the standard deviation (SD) of the elevation and the slope.
Land cover variables are mainly related to the erodibility (vulnerability to water erosion) of the soil subsequent to anthropogenic activities causing sedimentation. The land cover variables were calculated from a SVM classification based on Gray-Level Co-occurrence Matrix (GLCM) texture

Variables	Unit	Min.	Max.	Mean	RI
Physiographic variables					55.45
Mean Slope	°	7	33	23	14.12
SD slope	°	10	19	14	14.07
SD elevation	m	22	245	127	12.41
Mean elevation	m	11	322	146	7.03
Windwardness	%	4	92	44	6.17
Total surface area	ha	19	1359	228	1.65
Land cover variables					36.42
Built-up area	ha	0	115	13	15.37
Cultivated ar.	ha	1	150	18	11.24
Grassland ar.	ha	0	28	4	3.50
Shrubland ar.	ha	0	60	14	3.46
Invasive plant ar.	ha	4	257	47	0.86
Forest ar.	ha	6	1123	173	0.85
Non-native plant ar.	ha	7	468	79	0.71
Native plant ar.	ha	6	682	111	0.43
Sociological variables					8.12
Fishermen rate	-	1	5	-	5.78
Farmer rate	-	1	5	-	1.73
Population density	-	1	5	-	0.61

Table 1: Relative influence (RI) of the explanatory socio-ecological variables to the modeling of the RHI score. The RI of the variable clusters is the sum of the RI of the individual variables encompassed in the clusters.

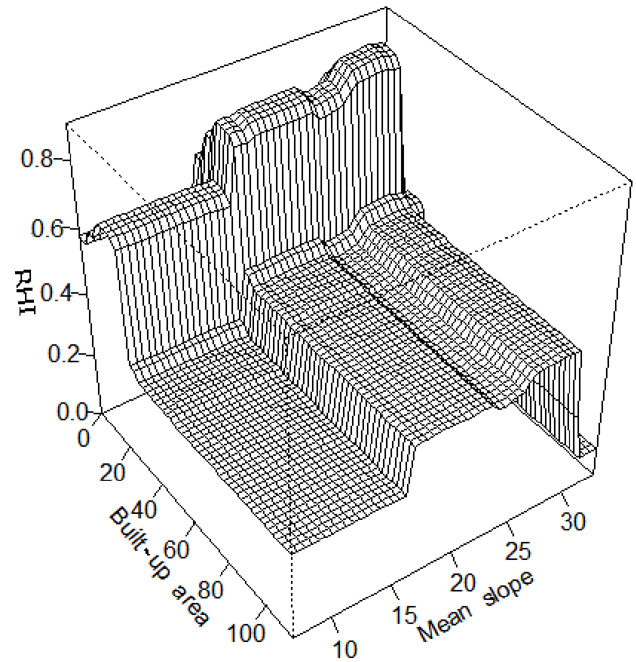

Figure 2: Joint partial dependence plots between the RHI score and explanatory variables provided with the largest RI.

metrics extracted from each band of the QB2 scene in 3 x 3, 9 x 9 and 15 x 15 pixels windows and an extensive field survey to collect reference data (see [8] for further details). From this map, we calculated the built-up area, the cultivated area, the area dominated by native, non-native (Polynesian and European introductions) and invasive plants (widespread European introductions) as well as area dominated by trees (>5 m), by shrubs (1-5 m) and by grasses (<1 m).

2.4. Statistical modeling

The RHI was the dependent variable we aimed to model from the independent socio-ecological variables. Multiple regressions were carried out with Boosted Regression Trees (BRT) [9]. Analyses were performed with the *dismo* package [10] developed under the R software [11]. A BRT model was built using the *gbm.step()* function (tree.complexity = 9, learning.rate = 0.01, bag.fraction = 0.5 and max.trees = 2000) from 37 randomized watersheds (67%) and its accuracy was assessed on the 18 remaining watersheds (33%). Then we computed the Relative Influence (RI) of each variable in a full model (with the 55 watersheds) using the *summary()* function [10].

3. RESULTS

The BRT yielded an AUC (Area Under the ROC Curve) of 0.74 indicating that the fitted model was fair. The RHI was primarily driven by physiographic variables (RI = 55.45) and to a lesser extent by land cover (RI = 36.42) while sociological variables were poorly contributing (RI = 8.12) (Table 1). Although land cover variables were secondarily influent, the most important individual variable was the built-up area (RI = 15.37). Watersheds with less than 20 ha of built-up area harbored a coral cover in good condition with an RHI in the range 0.5-0.8 and beyond this threshold the RHI rapidly dropped to 0.1-0.4 (Figure 2). Physiographic variables with the highest RI included the mean slope (RI = 14.12) followed by the dispersion of both the slope (RI = 14.07) and the elevation (RI = 12.41). RHI was the highest for intermediate values of slope between 20 and 30°. Plant habit showed substantial influence on RHI but plant origin much less. The built-up area was not linearly correlated to the population density (r^2 = 0.05; *p*-value = 0.83) which had in contrast poor contribution (RI = 0.61).

4. DISCUSSION

The variation of the RHI that our model failed to capture might arise from the omission of a set of critical variables or some limitations of the marine and terrestrial thematic

mapping but do also suggest that distal anthropogenic activities have a severe impact on reef health on the island of Moorea.

Among the proximal forcing factors of the reef health, physiography and particularly the slope play a major role but it is complex to disentangle effects of topography from anthropogenic impacts. Indeed human activities are concentrated on flat areas which could clarify why the RHI is low where the mean slope is below 20°. Within the steepest watersheds with mean slopes above 30°, the fringing reef is likely to be mechanically affected by the inertia of the runoffs.

The predominant role of human in driving reef health suggested by the mean slope was confirmed by the built-up area as the most important individual variable in our model. Interestingly population density had contrariwise little impact which indicates that non-house buildings (hotels, industrial areas, harbors, airport), generally located in non-residential areas, are the main drivers. Other anthropogenic drivers include farming, fishing, deforestation and finally plant invasion. However, we think that the area occupied by invasive plants, whose effect on erosion has long been documented including on Pacific islands [12], was underestimated due to the inherent limitation of RS data to map sub-canopy species [13] and the overall deterioration of low- to mid-elevation forests irrespective of the origin of the dominant species [14].

We believe these results will be useful for the stakeholders to prioritize actions in the field and highlight that timely land management strategies including planned urban and agricultural development, reforestation and invasive plant control can substantially limit proximal drivers of reef damage on Pacific islands, which are already critically impacted by global environmental changes.

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