Coral bleaching, coral diseases, and protected areas in the Florida Keys

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Abstract

Given that thermal-stress events and disease outbreaks have caused extensive changes to the coral reefs of Florida, it is imperative that we understand spatial patterns of bleaching and coral disease and examine their inter-relationship. This study used a probabilistic, two stage, stratified-random survey design to assess the condition of stony corals every summer from 2005 to 2010, at 1176 sites. All coral colonies > 4 cm were identified to species and their diameters were measured within replicated 10-m^2 belt transects. Each coral colony was also examined for disease and bleaching. This study tested the hypothesis that that there is a positive relationship between coral bleaching and coral disease in the Florida reef tract. The main objectives of this study were to: (1) examine the spatial patterns of coral bleaching and coral diseases, (2) determine which localities had the lowest bleaching and lowest disease prevalence, and (3) determine where in the Florida reef tract we can find abundant corals that have been subjected to minimal bleaching and disease and that are not given marine protection status. Coral colony densities and coral bleaching were highest on mid-channel patch reefs within the Keys. Disease prevalence was highest on the patch reefs and on the near-shore reefs of the upper Florida Keys. There was a significant correlation between bleaching and diseases, but the correlation was not strong (ρ =0.21). Few of the 'best' reefs, with relatively high coral densities and a history of low bleaching and low prevalence of coral disease, were within the boundaries of the regulatory zones of the Florida Keys National Marine Sanctuary (FKNMS). Protecting these so called 'best' reefs should be given local-protection consideration when rezoning the Florida Keys, because such action may preserve the potential seed-stock corals that will facilitate recovery, which will prevent further degradation of south Florida reefs under climate-change and more local stressors.

Rationale

Over the last three decades, coral reefs around the world have experienced major changes (Glynn 1993; Aronson et a. 2000; Hughes et al. 2003). The Florida Keys are no exception (Wagner et al. 2010). Reef corals have been subjected to unprecedented thermal stress events, which has led to extensive coral bleaching, diseases and mortality (Baker et al 2008). These events, in some localities have led to shifts in coral-community structure (Burman et al. in press). Over the next century, the climate is predicted to drive water temperatures to even higher levels, consequently increasing the risk of mass-bleaching events and disease outbreaks. Given that thermal-stress events and disease outbreaks have caused extensive changes to the coral reefs of Florida, it is imperative that we understand spatial patterns of bleaching and coral disease, and examine their inter-relationship.

Coral bleaching is a photo-inhibitive stress response to excessive irradiance and heat, and can be exacerbated by high concentrations of dissolved inorganic nutrients (Wagner et al 2010). These same stressors also lead to coral diseases (Muller and van Woesik, in press). It is therefore highly likely that bleaching and disease will be strongly related to each other, although they may be offset temporally. Therefore, **our hypothesis is that there is a positive relationship between coral bleaching and coral disease in the Florida reef tract.** The **main objectives** of this study were to: (1) examine the spatial patterns of coral bleaching and coral diseases, (2) determine which localities had the lowest bleaching and lowest disease prevalence, and (3) determine where in the Florida Keys we can find abundant corals that have been subjected to minimal bleaching and disease and that are not given marine protection status.

Methods

Sampling design of the Florida Reef Resilience Program

The sampling domain of southern Florida was stratified into 14 reef zones and 13 geographic subregions (Figure 1). Within this stratified domain, the primary sampling units were randomly selected 200-m x 200-m sites (following Ault et al 2006, Smith et al 2011). The number of sampling sites was weighted by the amount of available habitat. Sites were assessed at the second tier using two randomly selected transects, each of which was 10-m x 1-m. Sites were randomized *a priori*, and given to the boat captains as GPS points. Secondary localities were used whenever the primary localities fell over inappropriate habitats. Within each transect, each coral colony (>4 cm in diameter) was identified to species and its diameter was measured to the nearest centimeter, and examined for bleaching and disease. Bleaching intensity was assessed on an ordinal scale from zero to three, where zero corresponded to no bleaching, one corresponded to paling of all or part of the colony, two corresponded to bleaching of part of the coral colony, and three corresponded to bleaching of the entire colony. Each colony was also examined for the presence of diseases.

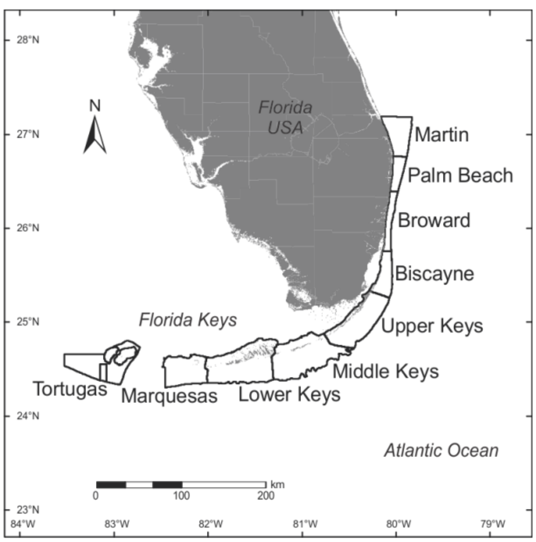

Figure 1. Spatial sampling framework of the Florida Reef Resilience Program (taken from Burman et al., in Press).

Sampling was re-randomized for each sampling period, which took place in the summers. Additional sampling was conducted after major thermal-stress events. There were nine sampling periods between August 2005 and September 2010. In total, 1176 sites were recorded.

We queried the data in Access® to compile: 1) the number of corals, 2) the degree of bleaching, and 3) the prevalence of disease. First, coral colony density was derived by summing the number of individual coral colonies within each transect. Second, coral colony diameter was measured at the widest point of each colony; these diameters were summed within each transect. Third, coral colony area was computed using the aforementioned diameters, and using the equation for the area of a circle:

$$A = \left(\frac{D}{2}\right)^2 * \pi ,$$

where *A* is the colony area, and *D* is the colony diameter. These areas were then summed for each transect. Fourth, coral bleaching was assessed as an ordinal variable (i.e., 0, 1, 2, and 3). The bleaching variable was summed for all colonies in each transect. Fifth, coral disease was quantified by summing the numbers of diseased colonies in each transect.

Given that the absolute amount of bleaching and disease both depend upon coral colony density, we sought to adjust for relative coral colony density. We accumulated the sum of the ordinal bleaching data for each transect. Similarly, the number of diseased colonies was also summed per transect. Notably, coral disease was not quantified on an ordinal intensity scale, but was quantified as either present or absent. We then divided the sum of bleaching intensity and the sum of disease by the number of colonies within each transect. The result was a mean per-colony bleaching intensity, and mean per-colony disease prevalence for each transect. Given that the smallest sampling unit was the site, one hierarchical level above transect, we took the mean of these per-colony values for the two transects within each site. The resulting data were exported, and attached to the coordinates of each site. These variables were analyzed for correlations using a series of Spearman's Rank Correlation tests.

Interpolation and correlations

The data were imported into ArcGIS 9.2, and georeferenced. We then interpolated each of the three datasets using a natural neighbor interpolation. After examining the output among the different interpolation procedures (i.e., inverse distance weighing, kriging, and natural neighbor), we found that the natural neighbor technique was most accurate, and best represented the data. We used the “extract by mask” tool to constrain the interpolations within the sampling domain (Figures 2, 3, 4). The layers contained continuous data, but we sought to classify the reefs in broader terms. Using the ArcGIS 9.2 “slice” tool, we generated three ordinal data classes from the interpolation raster files for (i) coral colony density, (ii) bleaching, and (iii) disease that were based upon natural breaks within the data (Figures 5, 6, 7).

In selecting habitats for protection within the Florida Keys, we wished to identify localities with (i) the highest coral density, (ii) the lowest bleaching intensity, and (iii) the lowest disease prevalence. In order to find these areas, we needed to first reclassify the data. All three “sliced” raster files were further simplified. We needed to determine which reefs had the highest coral colony densities, the lowest prevalence in disease, and the lowest bleaching. For this purpose, we used the “reclassify” tool in AcrGIS 9.2, whereby reefs with low (i.e., 1) to medium (i.e., 2) density were reclassified to zero, and the reefs with the highest coral densities (i.e., 3) were reclassified to one. For the bleaching and disease data (i.e., which were raster files at this stage in the analysis), we wanted to find the reefs with most bleaching and disease so that we could eliminate them from consideration for protection. We again used the "reclassify" tool, this time, the least bleached or diseased reefs (i.e., 1) were reclassified with a 0. Reefs with either medium (i.e., 2) or extensive (i.e., 3) bleaching or disease were reclassified as 1 (Figures 8, 9, 10). Finally, we used the "minus" tool within ArcGIS 9.2 to subtract the bleaching and disease layers, generated by the reclassify tool, from the coral-colony density layer. This resulted in a scale of priority from -2 to 1. A value of 1 highlighted reefs with abundant coral and a history of minimal bleaching and low disease prevalence.

Results and Discussion

Colony densities, coral bleaching and diseases

Coral colony density, coral bleaching, and the prevalence of coral disease were all greater within the Florida Keys than they were at sites farther north, although the prevalence of disease was also high in Palm Beach and Broward Counties. Coral colony density and coral bleaching were highest on patch reefs within the Florida Keys (Figures 2 and 3). Disease prevalence was highest on the patch reefs and on the near-shore reefs of the upper Florida Keys (Figure 4). There was a significant correlation between bleaching and diseases, but the correlation was weak (ρ =0.21) (Table 1). One possible reason for the relatively weak correlation is that bleaching often precedes disease outbreaks by one or two months (Muller al et. 2008). Therefore, the survey reported here, conducted over a short period every summer from 2005 to 2010, would not detect the temporal lags between coral bleaching and disease outbreaks. We note that the Marquesas was also sampled, but only at 6 sites, because sampling was weighted by area. Therefore, the information for the Marquesas is inconclusive.

Protection

To synthesize the intricacies of the data layers for the Florida Keys, we compressed the data to an ordinal code. A value of one indicated high densities of coral colonies and low bleaching and disease. A value of zero indicated one of two possibilities: a) low colony densities, low coral bleaching, and low disease prevalence, or b) high densities and high bleaching or disease. A value of negative one indicated either: c) high colony densities and high bleaching and disease, or d) low colony densities and high bleaching or high disease. A value of negative two indicated: e) low colony densities with high bleaching and disease (Table 2, Figure 11).

We overlaid the current protected areas within the Florida Keys National Marine Sanctuary (Table 2, Figure 11). Protected areas coinciding with negative values could be considered for rezoning because they are not optimal locations to protect corals, at least based on the extrinsic factors such as return frequencies of thermal stress that cause coral bleaching and disease. Similarly, protected areas coinciding with zeros should be considered low priority areas for coral protection. Localities classified as a one in our analysis, could be considered for protection status (Figure 11).

The majority of the reefs currently protected within the Florida Keys National Marine Sanctuary could be considered for rezoning, at least in accordance with our analysis that focuses specifically on corals. Grecian Rocks, Tennessee Reef, Coffins Patch, and Looe Key fall within the highest priority reef area (Table 2, Figure 11). Furthermore, localities between Tennessee Reef and Sombrero Reef, southeast of Marathon and Long Key, in the middle Florida Keys, and the area between Looe Key and Eastern Sambos in the lower Keys supported some of the 'best' contemporary coral reefs, defined as reefs with relatively high coral colony densities and with a history of low bleaching and low prevalence of diseases. In the upper Keys, there is a small area supporting relatively high coral colony densities and with a history of low bleaching and low prevalence of diseases, between Grecian and Fowey Rocks (Figure 11). In combination, these areas should be considered high priority areas and should be given particular consideration when the Florida Keys are rezoned. These recommendations, however, do not suggest anything about the efficacy of marine protected areas in the Florida Keys, because our study merely examined the large scale extrinsic factors that influence corals in the Florida Keys.

Conclusions

We show that the reefs in the Middle Keys have relatively high coral colony densities and have a history of low bleaching and low prevalence of diseases compared with other reefs in the Florida Keys (Figure 11). Yet, in the Middle Keys, patch reefs are few and coral reefs are less developed than they are elsewhere in the Florida Keys (Ginsburg and Shinn 1964; Marszalek et al. 1977). The constant flushing of the less than optimal waters from Florida Bay into the Middle Keys appears to have been inimical to reef growth (Ginsburg and Shinn 1964); however these same waters may reduce irradiance and therefore may buffer corals from excessive thermal stress. Although such ideas are speculative and need further research, it is interesting that the naturally high concentrations of suspended particles also reduced coral bleaching on the near-shore reefs of Palau in the Pacific Ocean (van Woesik et al. 2012). In conclusion, the area between Tennessee Reef and Sombrero Reef, in the middle Florida Keys, and the area between Looe Key and Eastern Sambos in the lower Keys supported some of the 'best' contemporary coral reefs, with abundant corals that have been subjected to minimal bleaching and disease.

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Table 1. Spearman's rank correlation analyses, where the correlation coefficient is denoted by ρ, the p-value is denoted by p, and number of sites is denoted by N, for coral colony density, colony size, coral-colony surface area coverage, disease prevalence, coral-colony density adjusted disease prevalence, and the extent of coral bleaching.

		Colony Density	Coral Colony Diameter	Coral colony Area	Disease Prevalence	Density Adjusted Disease	Bleaching
Colony density	p-value						
	N	1176					
Diameter	ρ	0.803					
	p-value	***					
	N	1173	1173				
Area	ρ	0.644	0.948				
	p-value	***	***				
	N	1173	1173	1173			
Disease	ρ	0.224	0.258	0.231			
	p-value	***	***	***			
	N	1176	1173	1173	1176		
Density Adjusted Disease	ρ	0.188	0.23	0.208	0.994		
	p-value	***	***	***	***		
	N	1176	1173	1173	1176	1176	
Bleaching	ρ	0.626	0.558	0.463	0.213	0.191	
	p-value	***	***	***	***	***	
	N	1176	1173	1173	1176	1176	1176
Density Adjusted Bleaching	ρ	-0.019	0.051	0.061	0.08	0.087	0.706
	p-value	ns	ns	*	**	**	***
	N	1176	1173	1173	1176	1176	1176

where ***denotes significance <0.001, ** denotes a significance of 0.01, and * denotes a significance of 0.05.

Table 2. Table of conservation priority that was identified in our analysis for reefs with current marine sanctuary, where 1 is high and 0 is low priority. ID numbers correspond to the labels in Figure 11.

ID	Name	Priority
0	South Carysfort	≤0
1	The Elbow	0
2	Dry Rocks	0
3	Grecian Rocks	1
4	French Reef	<0
5	Molasses Reef	<0
6	Conch Reef	≤0
7	Conch Reef*	≤0
8	Hen and Chickens	<0
9	Davis Reef	0
10	Cheeca Rocks	<0
11	Alligator Reef	<0
12	Tennessee Reef*	1
13	Coffins Patch	0-1
14	Sombrero Key	0
15	Newfound Harbour Key	<0
16	Looe Key*	1
17	Western Sambos	<0
18	Looe Key	≤1
19	Eastern Sambos*	≤0
20	Eastern Dry Rocks	0
21	Sand Key	0
22	Rock Key	<0

* Denotes research only area

Figure 2. Natural neighbor interpolations of coral colony densities in the Florida Keys.

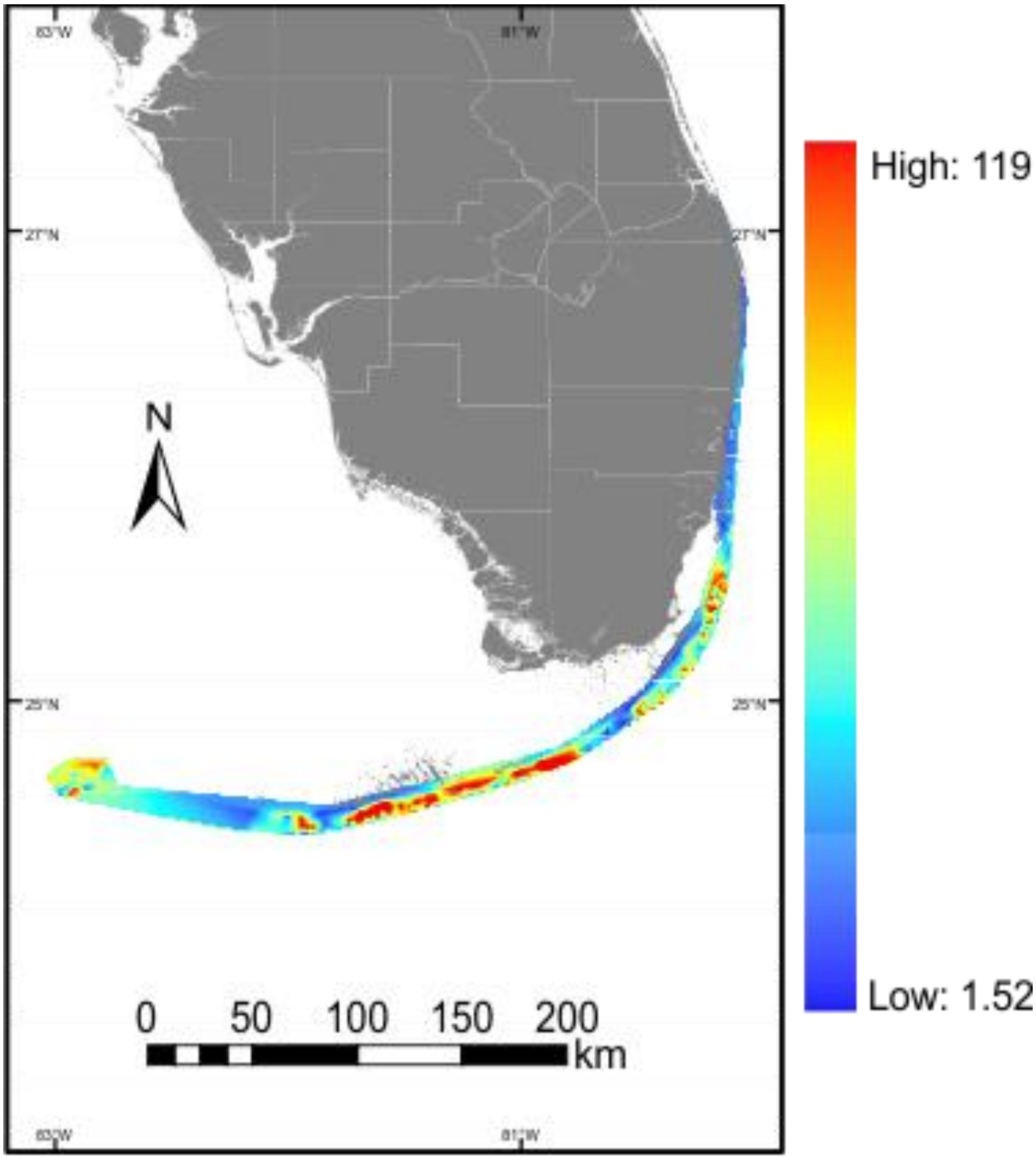

Figure 3. Natural neighbor interpolations of coral colony bleaching in the Florida Keys.

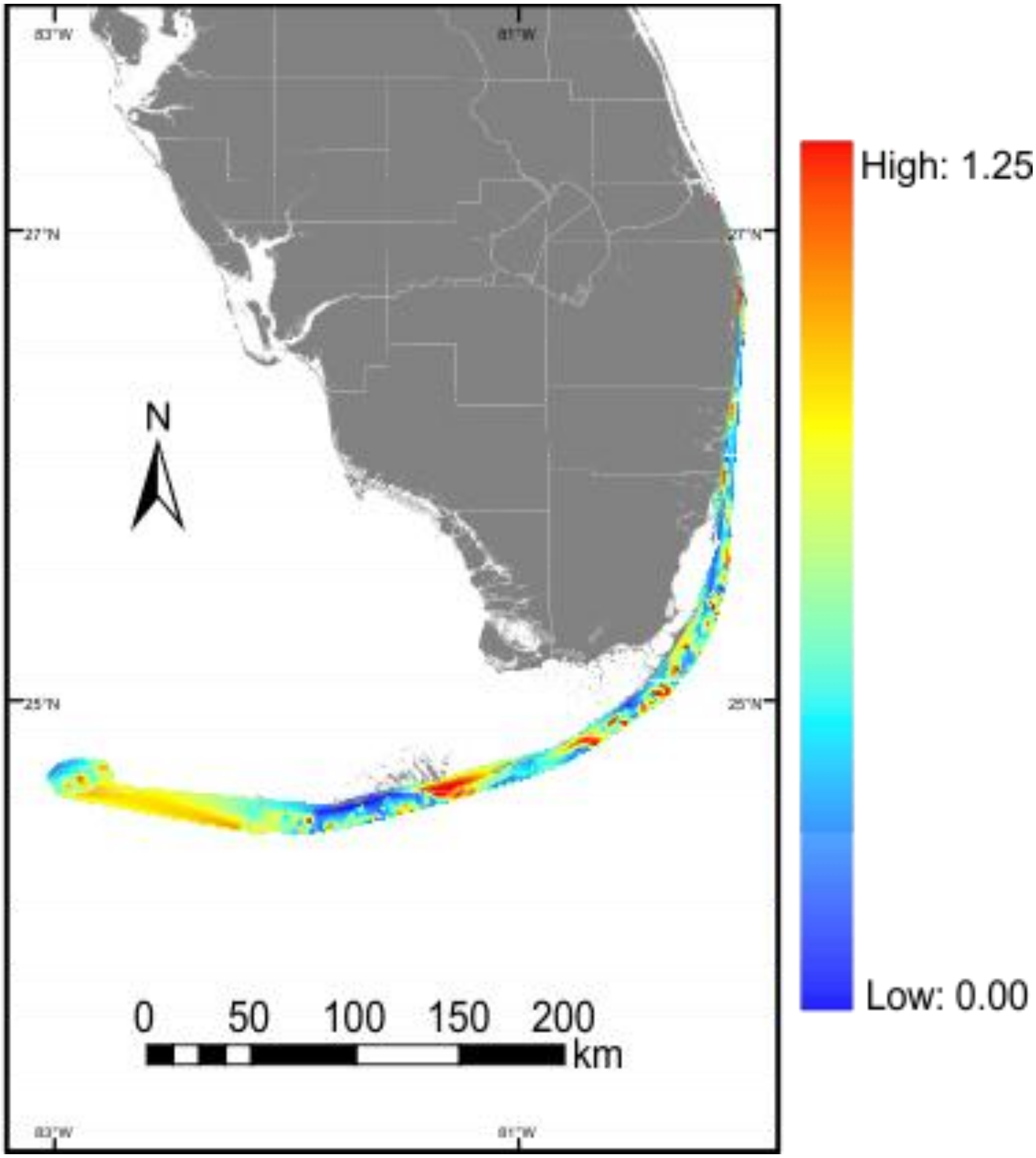

Figure 4. Natural neighbor interpolations of disease prevalence on coral colonies in the Florida Keys.

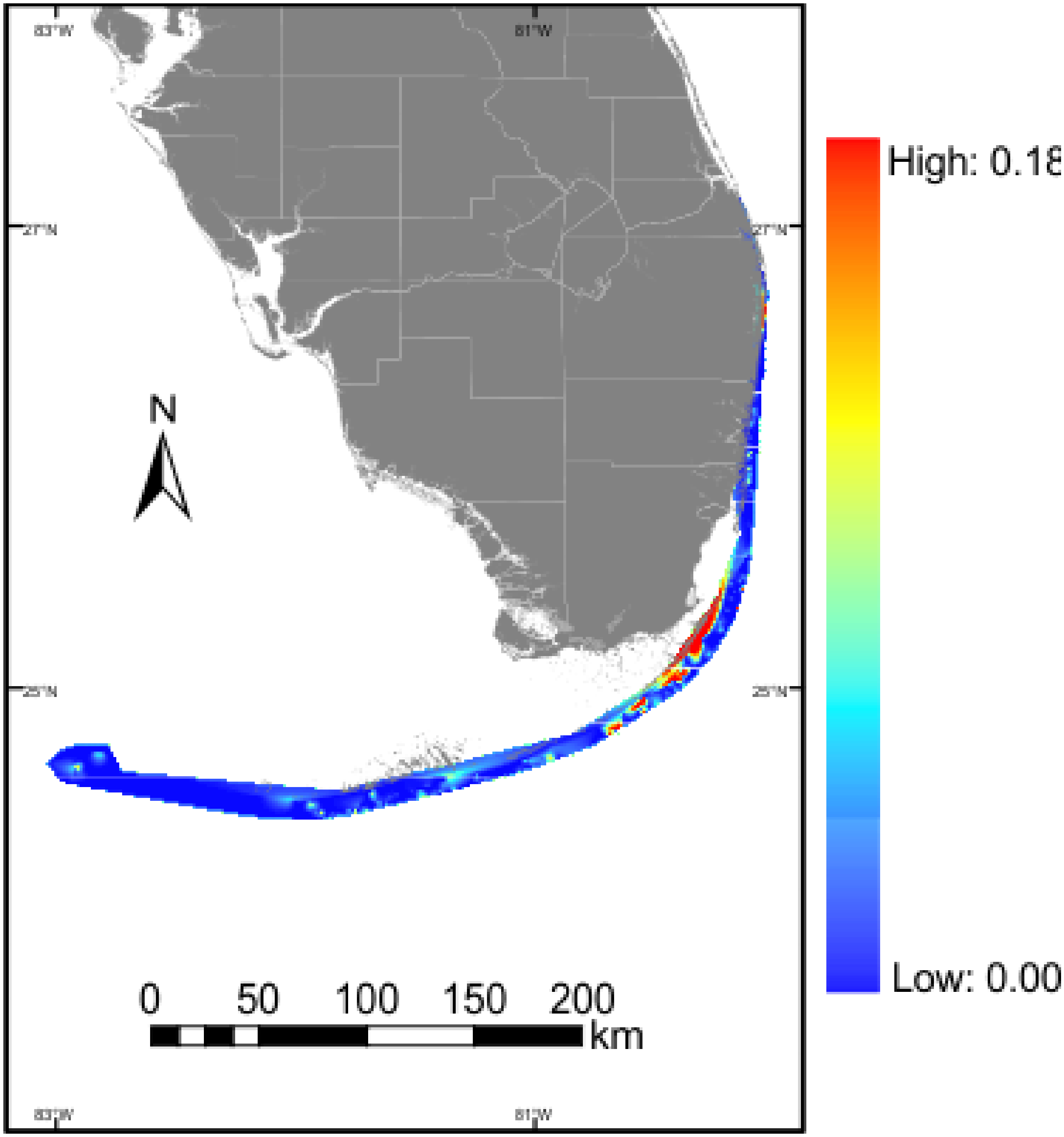

Figure 5. Abundance interpolations, after being "sliced" at natural breaks within the data, where (1) corresponds to the least abundant areas, (2) to moderate coral abundance, and (3) to maximum coral abundance.

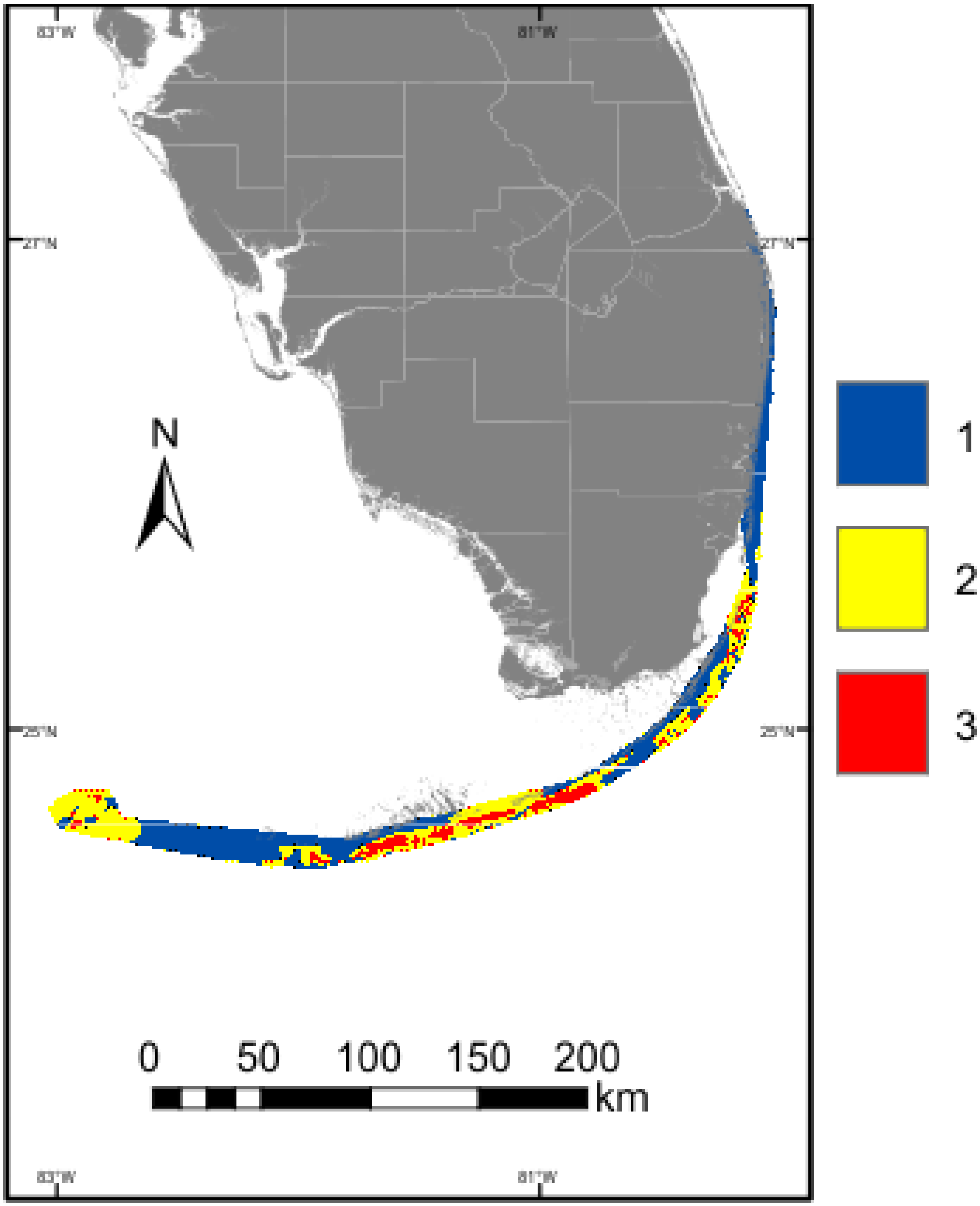

Figure 6. Bleaching intensity interpolations, after being "sliced" at natural breaks within the data, where (1) corresponds to the least bleached areas, (2) to moderate coral bleaching, and (3) to maximum coral bleaching.

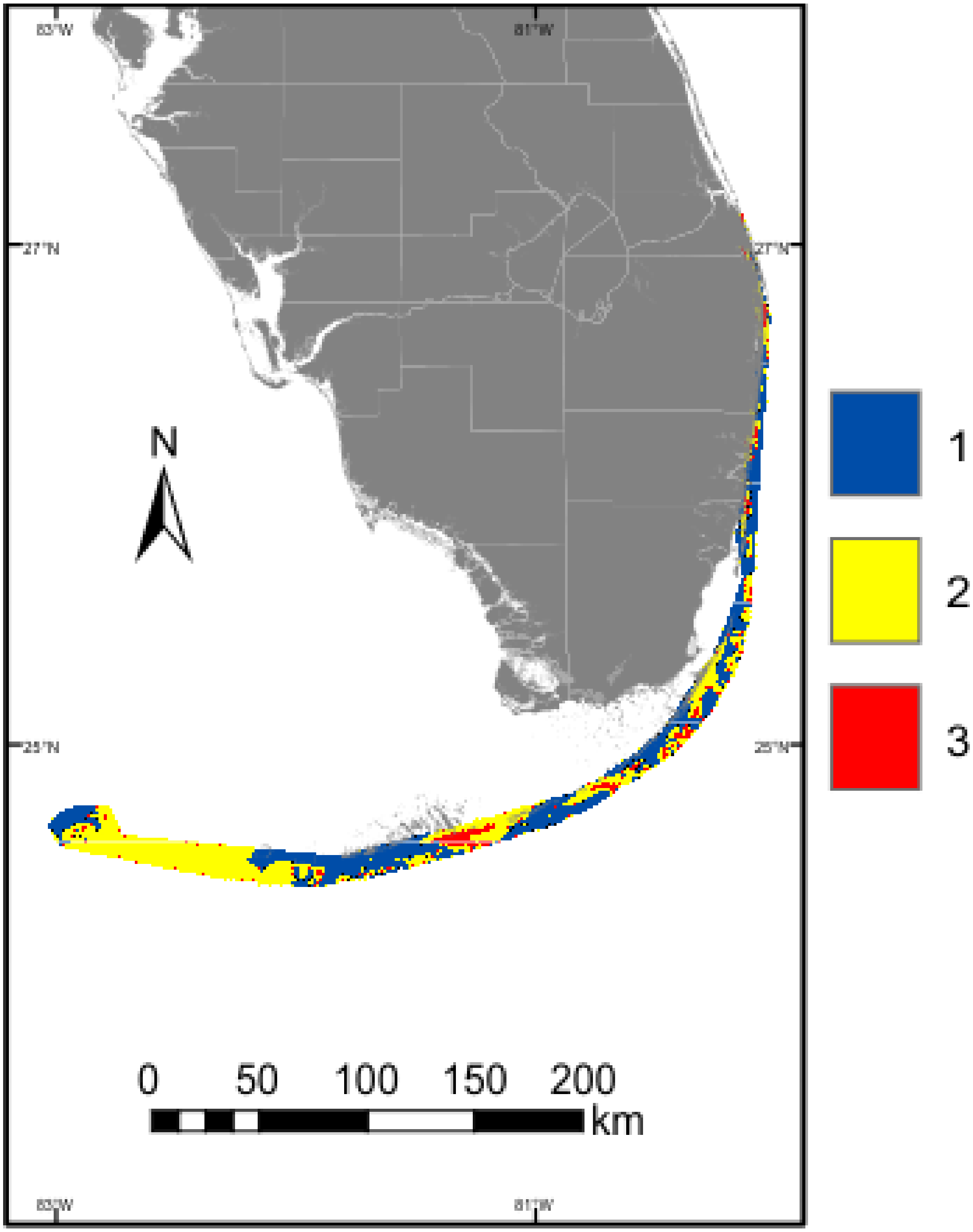

Figure 7. Disease prevalence interpolations, after being "sliced" at natural breaks within the data, where (1) corresponds to the least diseased areas, (2) to moderate coral disease, and (3) to maximum coral disease.

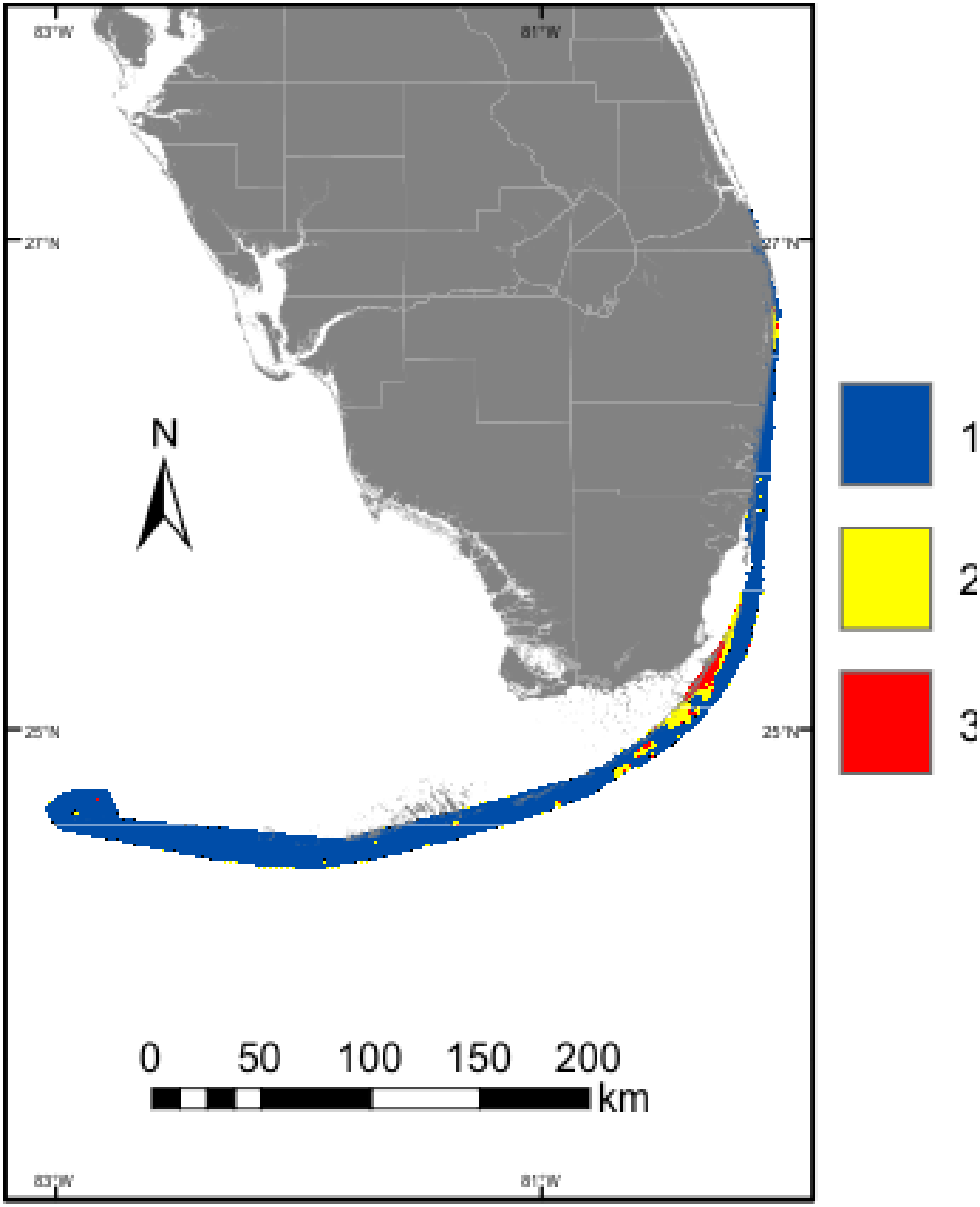

Figure 8. Reclassified data from the “sliced” density raster file. A value of (1) corresponds to the value of (3) in the “sliced” raster, while a value of (0) corresponds to a (2) or (3) in the “sliced” raster.

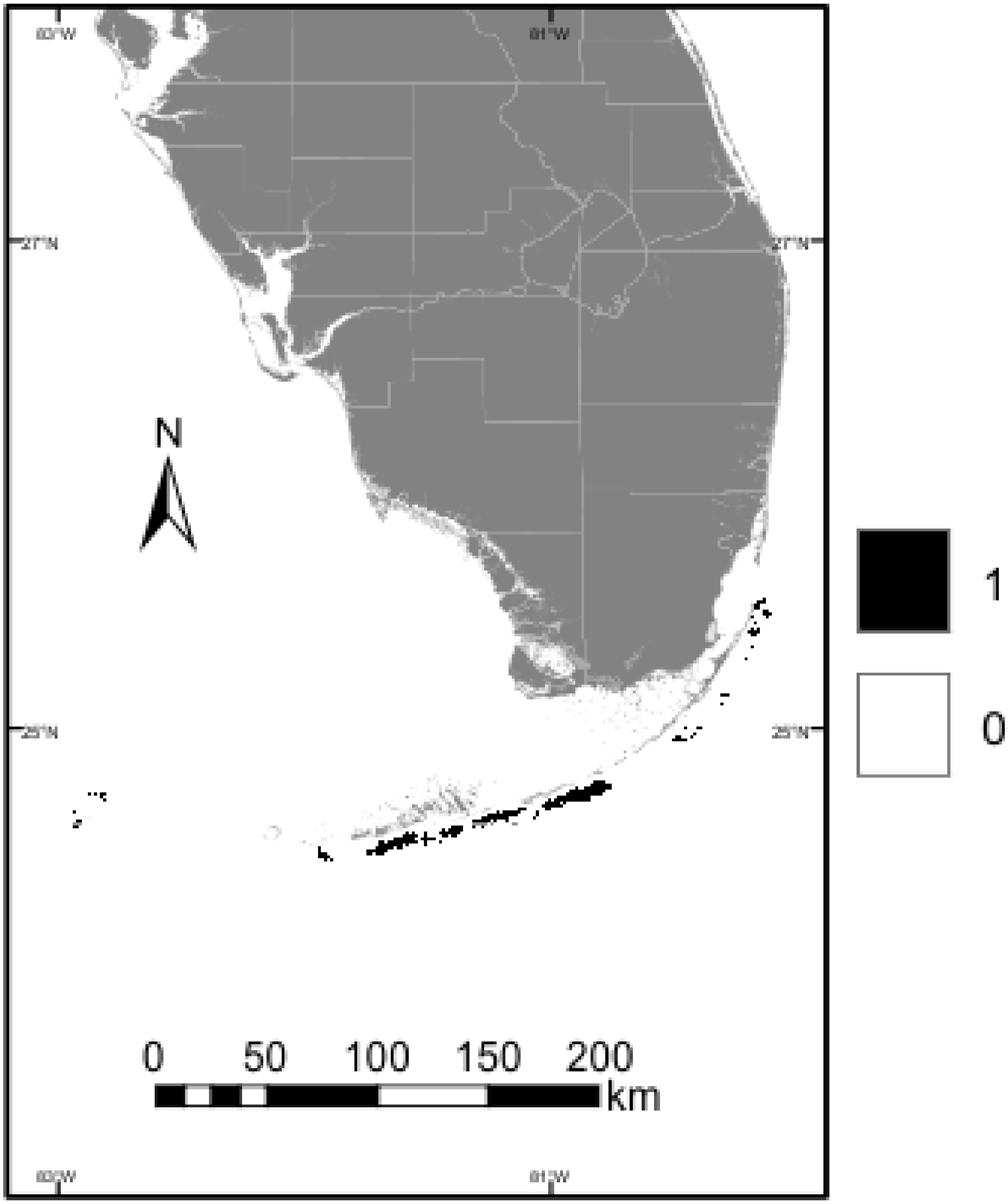

Figure 9. Reclassified data from the “sliced” bleaching raster file. A value of (1) corresponds to the value of (2) or (3) in the “sliced” raster, while a value of (0) corresponds to a (1) in the “sliced” raster.

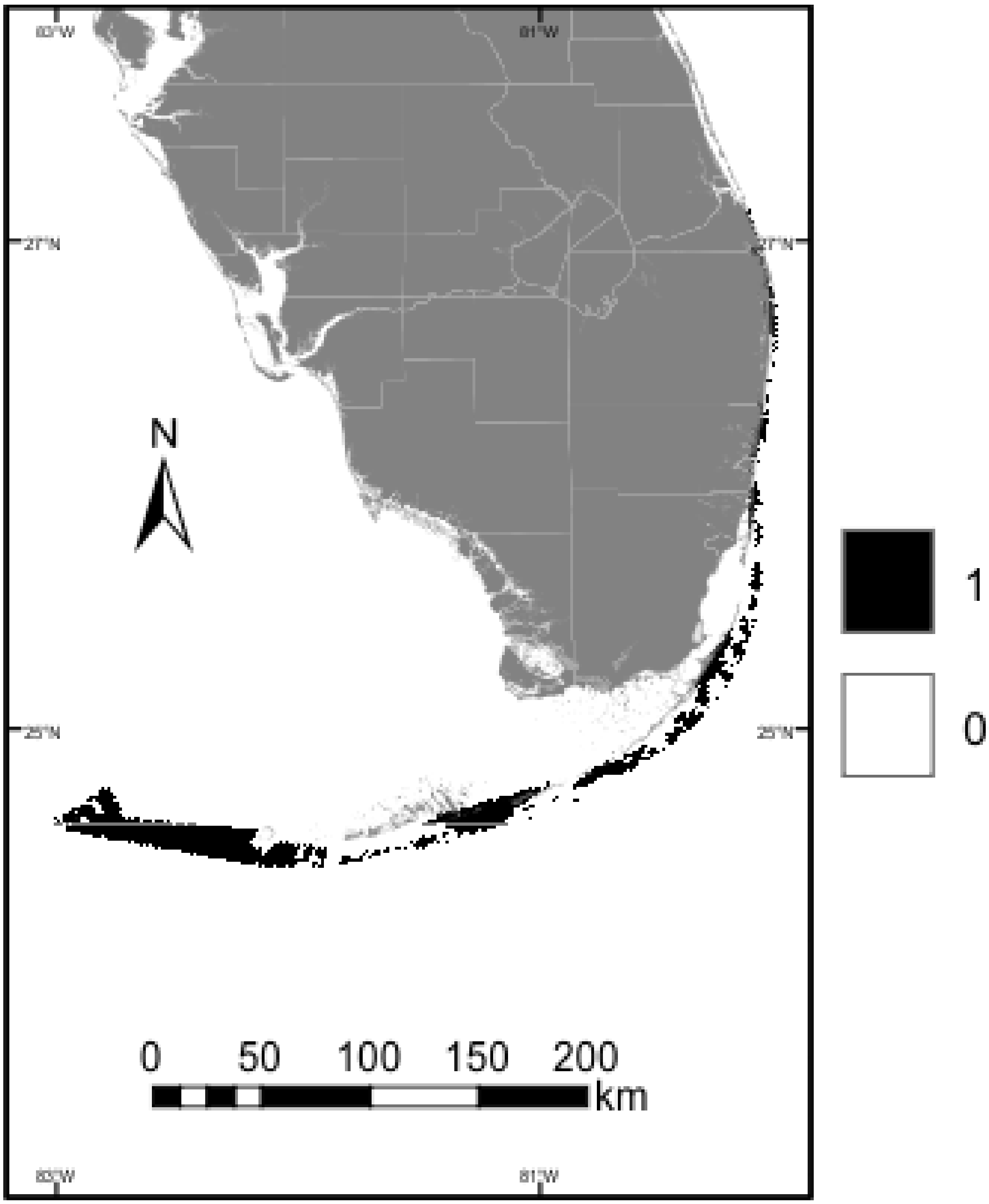

Figure 10. Reclassified data from the “sliced” disease raster file; a value of (1) corresponds to the value of (2) or (3) in the “sliced” raster, while a value of (0) corresponds to a (1) in the “sliced” raster.

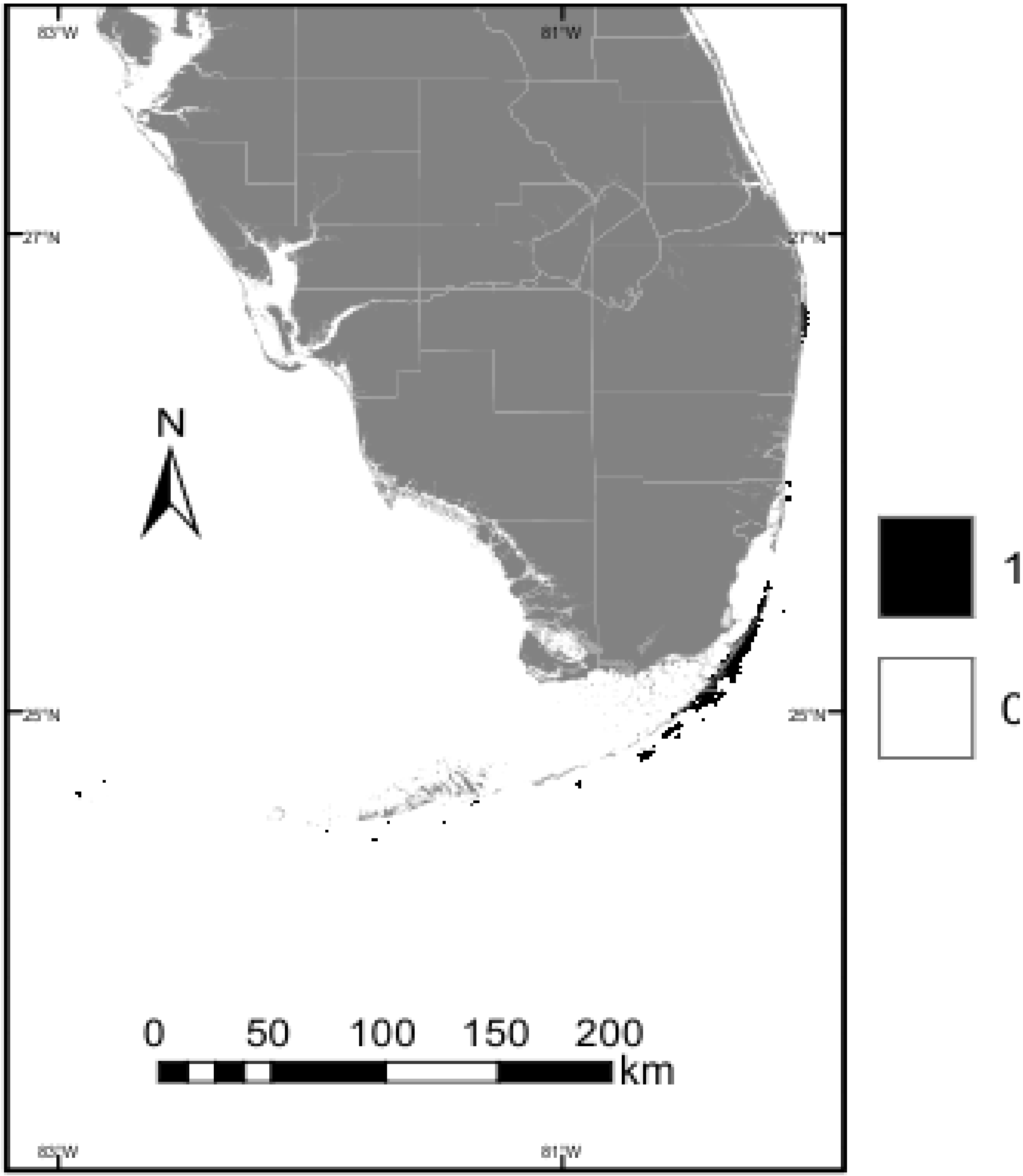

Figure 11. Florida Keys overview, where the green (1) are the localities that have high coral coral-colony density, and where bleaching has been relatively low, and coral disease prevalence has been low. Reefs marked in green are those reefs with the highest coral colony density, and lowest disease and bleaching, which should be considered for protected based on our model. Marine protected areas are labeled with numbers corresponding to Table 2.