

Point-by-point reply to reviewers' comments (reviewer comments in bold):

Note that much of the text developed in our published, detailed responses to the reviewers was incorporated into our revised manuscript. However, we have removed much of that detailed discussion from this response to avoid repetition where possible, and to focus on the specific locations in the manuscript where improvements have been made. We feel that all of the reviewers' comments have helped us greatly improve the paper. We have added all of the references recommended by the reviewers as well as those indicated in our published responses to the reviewers, and discussion of those references in context with our results. We have rewritten the methods and substantial pieces of the discussion as recommended by reviewers, and we have moved the technical data analysis procedures to a supplementary methods section. We have also added 6 figures that further explain our methods and support our results. As recommended, we have moved many of the Tables from the Supplemental section to the main paper to support our description of the methods. We have also included a conclusions section. Point-by-point replies to all reviewers' comments and specific page and line number references to changes are below.

Reviewer 1

Page 1, Line 1 : All dictionaries define 'sea floor' as 'the bottom of a sea or ocean'. Accordingly, using this term to describe the Pre-Holocene bed rock that underlies a coral reef body and forms its foundation is inappropriate.

The page and line reference for this comment refers to the manuscript title, which makes no reference to Pre-Holocene (or Pleistocene) bedrock. In Section 2.4 'Lower Florida Keys – volume to Pleistocene bedrock', we discuss the thickness of the Holocene reef layer lying above Pleistocene bedrock. The Pleistocene bedrock lies buried below the surface of the seafloor except for where it is exposed in some places. We have added a more detailed discussion of the formation of Pleistocene bedrock and its relation to the Holocene Reef formation of the Florida Keys on page 25, lines 5-24.

Page 3, Line 17 : I question the use of 'the number of people living close to the reef sites' as a parameter for anthropogenic impacts. Is the number of inhabitants the reflection of the local human activity (fishing, : : .) ?

We have reworded this section to only indicate that population has doubled over the time period of our study at each populated study site on page 5, lines 19-22. We have also added information on trends in live coral cover and other indicator species as evidence for anthropogenic impacts on page 4, line 20 – page 5, line 5.

Page 12, Line 16, about 'the coral-dominated habitats' : It would be useful to have some information about the living coral cover. This will inform the debate on the real state of health of each studied reef site.

We have provided a summary of changes in live coral cover, diadema sea urchin densities, parrotfish biomass, and macroalgae cover in a paragraph on page 4, line 20 – page 5, line 5. We have also included table 1, that summarizes results of this discussion.

Page 14, Line 8 : about the chronic erosion processes. These are natural processes affecting reef systems. Reef growth reveals to be the subtle balance between constructional and destructional processes. They occur continuously on both pristine and degraded systems.

We fully agree and make no statement to the contrary. In the cited paragraph, our aim was to make the point that our estimates of seafloor elevation change reflect the net result of all constructional and erosional forces affecting these regions. We have included more detail in our discussion on pages 19-20 regarding both the advantages and limitations of the methods we used in our study, and we have also included a list of key limitations in the conclusions section on page 27, lines 1-7.

Page 14, Lines 20 – 21 : It is clear that reefs that are located closed to urban areas are suffering significant deterioration. It would be interesting to compare these results with a reef system located in a remote and not inhabited area.

We agree. With the exception of Buck Island (which is uninhabited, but not remote), we were unable to locate sufficient historical and contemporary bathymetric data to perform our analysis in more remote, uninhabited locations. We would be very interested in such a comparison as well.

Page 14, Lines 26-27-28 : about the assertion 'n coral reefs in all three regions will be unable to keep up: : : : : (Church et al., 2013) 'z. This is an overinterpretation of the data presented herein. Using mean rates of reef accretion established at the scale of the Atlantic and Pacific to infer future responses of reefs to the rise in sea level is not receivable. A number of previous studies worldwide indicated that vertical reef accretion varies from site to site in a given region. There, some reefs will be able to maintain pace with sea level, while others will be unable to compensate for sea level rise.

We gave rewritten this section, now on page 21, lines 31-34 to indicate that our study sites, specifically, we be unable to keep pace with rising sea level. We have also included discussion of studies showing coral reef islands and ecosystems that are keeping up with rising sea level including work by Kench, McLean, Hopley and Kinsey on page 22, line 26 – page 23, line 15. We compare results from these studies with observations from our study sites.

Page 15, Line 29 and Page 20, Line 23 : Please correct the reference : Neumann and Macintyre, 1985

We found numerous reference errors in our original manuscript to due problems with End Note conversions. We believe we have now corrected all of these errors.

Reviewer 2

General comments:

Both the scientific quality of the paper and its presentation quality are generally insufficient.

The scope of the paper, as it is formulated pages 2 and 3, i.e. “measuring changes in seafloor elevation to assess and predict the impact of reef degradation on the vulnerability of coastal communities to sea-related hazards” is confusing.

We have rewritten this section, now located on page 3, line 11 – page 4, line 2 to more clearly state the aim and scope of our study.

The title of the paper itself is also unclear.

We chose this title because it summarizes the major finding of our work, namely that seafloor elevation is decreasing (rather than increasing) while sea level is rising in the coral reef ecosystems we studied (thus, we use the term divergence); and the combination of seafloor elevation loss and sea level rise has accelerated the relative increase in water depth at these locations. The title of the paper is derived from our concluding statement on page 26, lines 19-21 of the revised manuscript.

“The divergence between rising sea level and declining seafloor elevation has already increased the risk to coastlines in these regions from long-term, persistent oceanographic pressures and periodic events such as storms.”

We have rewritten the title as “Divergence of seafloor elevation and sea level rise in coral reef ecosystems” to more accurately limit our conclusions to the sites we studied based on comments from Reviewer 2 regarding page 14, lines 26-28 in the original manuscript.

The authors announce that they address the coral reef issue and then they provide results on various habitats, including non-coralline habitats and even deep water offshore habitats (e.g., page 13, lines 3-5).

We have added a paragraph on page 4, lines 4-10 that states what we include in the coral reef ecosystems that we analyzed, as well as justification for including non-coral dominated habitats within these coral reef ecosystems.

Authors are unclear on what they measure, and on my view they fail in generating robust data (as both the data and the methods used lack accuracy. Thereafter, the presentation of the results and their interpretation are confusing, as various types of processes are invoked to explain changes, with no specific process being robustly studied (e.g. page 13, lines 30-34).

We have made a number of changes in the paper to help clarify the methods we used in the paper, and the rigor with which we evaluated accuracy and error associated with our results:

- 1) We have created and included a flow diagram (Figure 1 in revised manuscript) that depicts the core processing steps in our methods.
- 2) We have rewritten the methods in more detail and more clearly for a broader audience, and we have moved the technical data processing steps to a supplementary methods section.
- 3) We included Section 2.2 (page 7, lines 15-31) on the methods we used for preliminary inspection of historical data sets during the selection process, including an example figure of that process (Figure 2).
- 4) We included more detailed discussion on developing the elevation-change surface models used in our study and an example figure (Figure 3) to further illustrate the process. We have also included photographs from visual inspection of our study sites as supporting evidence for our discussion (Figures 8 and 9).
- 5) We have included more detail on the very rigorous data and error evaluation analyses that we performed including a detailed discussion of data resolution and allowances for historical and modern data (page 6, line 10 – page 7, line 13).
- 6) We also included methods and results for pavement analyses we performed to determine validity of comparing historical and modern data sets (page 13, one 25 – page 14, line 11) prior to beginning elevation-change analyses, and a figure of results from this analysis (Figure 4).
- 7) We have also modified our discussion of error calculations to better clarify these methods page 11, line 15 – page 15, line 20.
- 8) We have moved supplementary Tables S1, S2 and S3 that describe details regarding the data sources, data conversions and study periods for each study site to the main paper, now Tables 2, 3 and 4 in revised manuscript, to help further clarify our methods.

Additionally, we have added a detailed discussion emphasizing that a key limitation of our elevation-change analyses is that they do not attribute change to cause and that a detailed analysis of the processes causing elevation-change in these systems was beyond the scope of this paper. We explained that we provided general comparisons of our elevation and volume-loss measurements to individual process rates from the literature to provide context for the magnitude of our results. These comparisons also demonstrate the potential value of knowing net whole system change when accounting for and identifying individual processes, for identifying missing gaps in erosion/accretion budgets, and serve as an example of how our results may be used in future studies to improve erosion and accretion

budgets in coral reef ecosystems. This discussion is now located on page 19, line 24 –page 21, line 2 in our revised manuscript.

For example, the first paragraph of the Discussion Section clearly illustrates the wide (and unprecise) area covered by the paper (see page 14, lines 5-15).

We do not discuss the area covered by our study sites in this paragraph in the original manuscript. However, our study sites are very clearly defined on the maps in figures 1-3 of the original paper (now 6-7 in the revised paper) and the exact size of each study area as well as each habitat area within each study site is provided in Table 10 (in revised manuscript). The paragraph on page 14, lines 5-15 discusses the large number of processes that cause seafloor elevation and volume changes and the very general time frames over which they occur. We are, therefore, confused by this comment.

Both the concepts (“change in seafloor elevation and volume” – in fact, it seems that the authors address “changes in shallow waters depth”) and the method used (method “traditionally used to monitor seafloor changes”, “use of historical bathymetric data from the 1930’s to 1980’s and LiDAR DEMs from 1990’s to 2000’s) –which are presented firstly in the introduction of the paper (pages 2-3) and then in the Methods Section (page 4) – are questionable and not accurate.

We have now included a new section in the revised manuscript title “Section 2.1 Selection and description of data sets beginning on page 5, line 12. We provide a very detailed discussion of the cautions that must be applied when selecting appropriate historical and modern data sets for elevation-change analyses, as well as detailed information on the rigor and resolution with which these data sets were collected and QA/QCed.

Concerning data and methods - How can bathymetric data from the 1930’s to 1980’s (constituting a single coherent period reflecting low anthropogenic impact?) be considered as a starting point (or reference) to “measure changes in seafloor elevation” and then be compared with data from the 1990’s to the 2000’s (= period reflecting high anthropogenic impact?).

Each of our five study sites was analyzed independently over a specific time period using the oldest reliable data that we could find for each site as well as the most recent bathymetric data available for that site. We have clarified this in the revised manuscript on page 5, lines 13-22. We did not measure change over a continuous historic range of 1930’s to 80’s and modern range of 1990’s to 2000’s. For example, the Upper Florida Keys historic data set was from 1934 and 35, and the modern data were from 2002. The dates for the individual data sets are now available in Table 3 of the revised manuscript. The aim of the study was to look at change in seafloor elevation over several decades. Within the time frame of the study, population approximately doubled at each of the populated study sites (with the exception of uninhabited Buck Island).

R2: This raises several key questions. Firstly, how can the “magnitude of erosion” (page 3, line 9) be measured using such an approach that poses serious questions relating to the scientific quality of both the datasets and the method used. In other words, how can historical bathymetric data be compared with LiDAR data? The former (bathymetric data from the 1930’s and next decades) do not have the required resolution for comparative measurements to be undertaken with LiDAR data. The low resolution of historical bathymetric data may generate significant errors in the results generated. Incidentally and curiously, no clear and complete information is provided by the authors on the resolution of the various datasets used in this study at the various study sites.

We have now included detailed information on the resolution of the historical and modern data on page 6, line 11 through page 7, line 13. We have also included methods and results for pavement analyses that we used to show the validity of comparing historical elevation data to modern LiDAR elevation data, Section 2.12, page 13, line 25 – page 14, line 11. We have also included point density information for the historical data sets on page 8, lines 26-28, and note the potential impact of point density on error in these data sets. We prove through both vertical and horizontal error analyses the potential impact of these errors on our results in sections 2.11, 2.12, and 2.13 on pages 11-15, and confirm the statistical significance of our elevation and volume calculations.

Authors first indicate a 1 to 4 m horizontal spatial resolution (this is a low resolution that do not allow the calculation of changes in the reef level) and then indicate a 11-12 cm vertical resolution (which is questionable given the data used).

The 1 to 4 m horizontal resolution applies to the LiDAR data sets only. We calculated horizontal error for the oldest historical data using published values for the methods (section 2.13, beginning on page 14) of 4.8 m. To estimate the effect of horizontal error on our seafloor volume results, we performed a horizontal shift analysis. For this analysis, we doubled our calculated horizontal error to 10 m, then shifted the historical data set relative to the modern data set by 10 m in each of the four cardinal directions (N, S, E, W) and recalculated volume change for each scenario. These results indicate that horizontal error of up to 10 m and the resulting offsets in sounding points affects our volume calculations by 10% to 21% (depending on density of data points) and does not change the outcome or conclusion of our study. These results are consistent with reports that, over large areas (such as in our study), random errors largely cancel-out relative to change calculations derived from two surfaces (Byrnes et al. 2002). Additionally, this analysis provides further evidence that seafloor elevation loss is occurring at a very broad-scale across all habitat types.

With respect to vertical resolution, the reviewer’s statement is incorrect. Nowhere in the paper do we claim vertical resolution of 11-12 cm. We believe the reviewer may be making reference to the VDatum transformation error that we report for each data set that is only one parameter used to calculate total error (see page 8, lines 30-32 and

Equation 1 in original manuscript, now in Section 2.11 beginning on page 11 of revised manuscript). We state the maximum cumulative uncertainty for operational VDatum regions of South Florida and the Virgin Islands are 9.6 and 11.8 cm, respectively as reported by the NOAA National Ocean Service. We also report the VDatum error that was calculated specifically for each individual study site under the RMSEVDatum column in Table 5 of the revised manuscript that ranges from 8.1 to 11.4 cm (note no VDatum error was reported for Maui because no VDatum transformation was required). Total vertical error for each study site was calculated using equation 3, reported in Table 5 under the column heading RMSETotal, and ranged from 20 to 37 cm (average of 29 cm for all sites). We used a very conservative approach in our consideration of vertical error by multiplying our RMSE_{Total} by a factor of 1.65 to encompass 90% of the variance in our data. This approach generated a more conservative RMSE of 0.48 m that we rounded up to 0.5 m; and we used this value to set minimum and maximum bounds in our volume calculations (Table 8 in revised manuscript). The minimum volume change values that we report in Table 8 were calculated by only including elevation changes that exceeded the range of -0.5 to +0.5 m to provide a very conservative estimate of volume change. These very conservative minimum volume change values also support our conclusions of net seafloor erosion at all study sites (Table 8 in manuscript).

A second methodological problem is raised by the way anthropogenic impacts are considered in this study. (1) How can the “anthropogenic impact” only be measured by population numbers? In the present case (changes in water depth), it mostly depends on coastal and maritime human practices (sustainable/not sustainable). Major human activities, such as dredging in the substratum (should it be coralline or not) and extracting aggregate in particular, which may have occurred over the study period at some study sites and may have changed water depth, are not considered at all by the authors, which introduces a serious bias in the “elevation changes measured”. Some parts of the paper, such as “However, greatest mean elevation losses occurred in coral-dominated habitats and near the central coastline where harbour and shipping channels exist” (page 13, lines 22-23) clearly indicate that not taking into account these human activities is problematic when assessing changes in shallow water depth.

This claim is incorrect. In fact, on page 14, lines 8-18 (first paragraph of our Discussion in the original manuscript), we specifically state that we DID include changes due to episodic events including, for example, dredging and infilling of channels and coastal harbors. This statement remains in our revised manuscript beginning on page 19, line 24. These changes were included in our analyses because they directly change seafloor structure and alter habitat distribution.

Generally, this paper mainly appears as a “technical” paper that describes the GIS procedure applied to calculate changes in elevation, without addressing in an adequate way the conceptual, and the data and methods aspects raised. It seems that authors do not have the required background to address the complex scientific question that they have chosen to address. The technical procedure described on pages 4-6 is in-

comprehensible to me. Despite the fact that I failed in understanding this procedure, my feeling is that the method is not robust due to poor conceptual, and data and method, bases.

We have rewritten the methods section to more clearly explain the concepts and procedures of our methods and analyses. We have added substantial discussion on the limitations of these types of analyses, and the value of considering elevation-change results alongside process studies to better understand and account for causes of physical change in seafloor structure. Our findings showing that the magnitude of regional scale seafloor erosion that has occurred in these systems has increased relative sea level rise causing water depths not expected to occur until 2100 are, in fact, very significant. We recognize that total erosion at the regional scale has likely been underestimated because no prior studies fully account for all processes causing elevation change in coral reef ecosystems; and we understand that our results may cause controversial feelings. However, we feel that we have proven the validity of our results and use of historical and modern data sets for our analyses with our expanded error analysis and our use of a very conservative RMSE for data calculations. Our conclusions regarding loss of seafloor volume are based on actual measurements of elevation-change shown to be statistically significant in over 90% of the habitats we analyzed, and that account for all of the processes causing elevation loss in these regions. We have moved the technical procedures to a supplemental section to improve readability of the main paper.

In different sections of the paper (e.g., page 13, line 1), the results obtained are correlated to generalities, e.g. on coral reef degradation, which is questionable. Results should be correlated to local data on reef health, including observed changes in living coral coverage, but not to worldwide observations. The interpretation of the results generated is not satisfactory: for example, the authors mention hurricanes as key controls of changes in depth. This raises the question of “what is measured, either long-term changes related to climate change and sea level rise, or changes due to low-frequency high-magnitude events”? Once again, this makes the paper confusing.

We have clarified in our discussion that our intent was to provide general comparisons of our elevation and volume-loss measurements to individual process rates from the literature to provide context for the magnitude of our results. These comparisons also demonstrate the potential value of knowing net whole system change when accounting for and identifying individual processes, for identifying missing gaps in erosion/accretion budgets, and serve as an example of how our results may be used in future studies to improve erosion and accretion budgets in coral reef ecosystems. This discussion is now included on page 20, lines 30-34 and beginning of page 21. We have also included reference to and discussion of more site-specific process studies for comparison to our studies, again to demonstrate the magnitude of our results and potential value of combining elevation-change analyses with process studies. See page 22, line 1 – page 24, line 14. Again, we emphasize that detailed study of the processes causing elevation change in these study sites was beyond the scope of the paper. We do, however, compare our results to observations of change and processes specific to these study sites. For example,

On page 18, lines 6-28, we note that a sub-region of the Upper Florida Keys showed a slight increase in elevation and that this location is near an area of the Middle Florida Keys that has been identified by Manzello et al. (2012) as a possible refuge from ocean acidification based on local data for that area. We reference work by Lidz et al. (2007) and Shinn et al. (2003) that corroborates our observation of accretion on spur-and-groove habitat due to burial by sand and evidence for redistribution of reef materials by hurricanes that has caused erosion in some areas and deposition in other areas of the Florida reef tract. On page 22, lines 7-10, we compare our erosion rate in the Upper Florida Keys to chemical erosion rates determined for the Florida Keys by Muehlllehner et al. (2016). All of these are examples of comparison of our results to local data on reef health and processes. We discussed that our methods and results account for both long-term changes over the time periods of our study as well as low-frequency, high-magnitude events in the first paragraph of our discussion.

Page 2, lines 28 to 30 are incomprehensible: “measures of total system change in seafloor elevation and volume are required to accurately assess and predict the impact of reef degradation on the vulnerability of coastal communities to hazards caused by storms, waves, sea level rise and erosion”.

We have clarified this passage to explain that hydrodynamic and other numerical models used to assess and predict the impact of reef degradation on coastal hazard vulnerability are limited by lack of comprehensive assessments of change in seafloor structure of coral reef ecosystems, on page 2, line 33 to page 3, line 2.

Page2, lines 31-32: “we quantify the combined effect of all constructive and destructive processes on modern coral reef ecosystems by measuring regional-scale changes in seafloor elevation” is incomprehensible.

We have rewritten this sentence to clarify, “Our study is based on the premise that elevation-change analysis measures the net result of all of the constructive processes that cause accretion (or increases in seafloor elevation) and the destructive processes that cause erosion (or decreases in seafloor elevation) on whole reef systems”, on page 3, lines 13-16.

Page 3: “we adapted an elevation-change analysis method that has traditionally been used to monitor seafloor changes”

We are uncertain as to the question regarding this statement.

Page 7, line 25 “sediment thickness of the Holocene reef deposit”: what do the authors talk about? Vertical sedimentation? Vertical Holocene reef building? The results exposed page 8, lines 11 to 14 for the Lower Florida Keys case study are incomprehensible to me. I do not understand how the authors “used a moderate reef age of 6000 years and a constant erosion rate” to “compute the time required to completely erode the remaining Holocene reef down to the Pleistocene layer”.

We have added a section describing the geologic setting of the Holocene reef deposit and Pleistocene bedrock of the Florida Keys, and we have expanded discussion of the methods to better clarify the concept and procedures we used for this analysis. See page 25, line 5 to page 26, line 4.

Page 8, lines 29-30: I am surprised to read that vertical errors would be comprised between 9.6 and 11.8 cm respectively, given what I know on LiDAR data and the horizontal error (1 to 4 m) applying to this study. More generally, I do not understand how vertical error estimation was conducted.

We have rewritten this section (now Section 2.11 beginning on page 11) to better define and clarify the error terms in our calculations, how they were derived, and calculation of total RMSE.

Page 12, lines 13 to 27– We understand that most study are not dominated by coral reefs, which means that this paper does not in fact address the pretended issue of reef response to changing environmental conditions. This suggests that the choice of study sites is not totally coherent with the objectives of the paper.

We have explained what we included in coral reef ecosystems within our study, as well as justification for including non-coral dominated habitats in our analysis on page 4, lines 4-10.

Page 12, lines 25 to 27: the conclusions drawn by the authors from the study of Buck Island correlates volume loss to sediment export. Both the results (volume loss) and the interpretation of the results (sediment export) are unclear to the reader.

We have expanded our discussion of the results from Buck Island and included figure 6 to support our discussion of volume loss, sediment export and how physical degradation of coral colonies can lead to volume loss without export. See page 17, lines 10-34 to beginning of page 18.

Page 14, lines 20-25: how can the authors convert “changes in elevation” into a “number of years of Holocene reef accretion”? This is not robust as coral reefs grow and erode over a given period, as a result of the complex imbricated processes driving both reef construction (i.e. construction) and sediment production (i.e. erosion allowing carbonate production).

The point of this exercise was to further demonstrate the significance of these losses. We have rewritten this paragraph to clarify and included more detail on this calculation including equations, see page 21, lines 4-34.

Bottom of page 15-top of page 16: I do not understand how the results obtained by the authors can be compared to the results of previous studies conducted by C. Perry to attribute observed changes to specific

drivers/processes.

Perry's 2015 paper is one of the most recent studies showing that while remote coral reefs that are largely isolated from human influence experience severe coral mortality from climate driven impacts like bleaching, most of these reefs recover very rapidly and continue to produce enough carbonate to keep up with present and future sea level rise. The C. Perry study was based on assessment of 28 reefs across the Chagos Archipelago reef system in the Indian Ocean. The point we are making here is that, although Maui is remote, it is not isolated from human influence; and our results showing large erosion rates suggest that these reefs systems have not recovered well from degradation and are not producing enough carbonate to keep up with rising sea level. We have rewritten a sentence on page 24, lines 25-28 to clarify this concept.

Page 15, lines 19-21: the estimation that “the total reef volume could completely erode down to Pleistocene-bedrock-surface in approximately 1250 years” is not well-founded.

AR: We have clarified our concept and procedure for this analysis and expanded discussion of the geologic setting on page 25, line 5 to page 26, line 4.

Page 15, line 33: “. . . reef systems. . . lack human impacts” is not correct in terms of style.

The terminology used in this sentence is from Perry's 2015 paper, and we are not certain as to what the reviewer is recommending here.

Page 15, lines 23-35: key references on reef islands future are not cited by the authors. See in particular the recent studies by Kench et al.

We have now included a detailed discussion on the future of reef islands on page 22, line 26 to page 23, line 15, and how their results differ from our observations in Maui. We have included the following references in this discussion:

McLean, R., & Kench, P. (2015). Destruction or persistence of coral atoll islands in the face of 20th and 21st century sea-level rise? *Wiley Interdisciplinary Reviews – Climate Change*, 6 (5), 445-463. 10.1002/wcc.350

Kench, P. S., Thompson, D., Ford, M. R., Ogawa, H., & McLean, R. F. (2015). Coral islands defy sea-level rise over the past century: Records from a central Pacific atoll. *Geology*, 43 (6), 515-518. 10.1130/G36555.1

Kench, P. S., Owen, S. D., & Ford, M. R. (2014). Evidence for coral island formation during rising sea level in the central Pacific Ocean. *Geophysical Research Letters*, 41 (3), 820-827. 10.1002/2013GL059000

Page 16, lines 3-5: an assumption like “Modern carbonate production rates are an order of magnitude lower than Holocene averages (Perry et al., 2013), and are estimated to decrease by as much as 60% by mid-century (Langdon and Atkinson, 2005)” is far too general.

These statements are not assumptions, rather they are derived from the field and experimental results of the cited studies. We do not use this data to quantify future responses of reefs, but rather to point out that carbonate production rates are projected to continue to decrease while bioerosion and chemical erosion are projected to increase in the future. These combined impacts are, in fact, likely to accelerate reef erosion rates. We have added reference to other studies that showed some reef systems will be able to maintain pace with sea level rise, along with the statement that “vertical accretion rates vary from site to site within a given region, some localized areas may continue accreting, and other coral reef ecosystems may be able to maintain pace with sea level rise”. See page 24, line 30 to page 25, line 3.

Tables 2 and 3 – The substrate categories included in these table are not presented and justified in the study. We additionally have not idea of the depth at which these habitats are situated.

This statement is incorrect. The habitat/substrate maps were discussed and referenced on page 6, lines 18-27 (now page 9, line 22 to page 10, line 6) and in the supplemental methods section. We have also moved tables 9 and 10 in the revised manuscript from the supplemental section. These tables list the habitats within each study site along with habitat area, and we have now included mean elevation (depth) data for each habitat in Table 9.

The maps provided page 30 indicate a complex spatial distribution of gains and losses, which is not described in the paper. They also show that shallow habitats were not totally covered, suggesting that gains may have occurred in non-covered areas that may compensate observed losses in study areas. This is all the more to be considered that the results obtained are contrasting (e.g. between the Central Sub-Region and the Lower Sub-region of the Florida Keys).

We have added a sentence on page 15, lines 26-25 specifically pointing to the complex spatial distribution gains and losses in our map figures (now 5, 6 and 7), to accompany our discussion of the range of elevation gains and losses we observed. We have included discussion of this distribution of data on page 20, lines 6-14 of our Discussion section.

There are gaps in the data coverage for the Florida Keys and Buck Island data sets and we have noted these in our revised manuscript on page 5, lines 16-19. We have also explained that our analysis was limited by the areal extent of available data sets. However, there is overwhelming evidence in the literature (as well as anecdotal evidence from field observations) that the trends we see in the areas covered by our data sets are consistent throughout the

surrounding areas outside of the boundaries of our study sites. We feel that our study areas in these locations are at a large enough scale to be representative of the broader region. We do not argue that there are some locations within our study sites that show accretion. For example, offshore, downslope areas where sediment is infilling spur and groove formations; areas shoreward of patch reefs where sediment from degraded coral reefs has been redistributed to deeper water habitat behind the reef; and, in the case of the Lower Sub-region of the Upper Florida Keys, a small area of increased elevation primarily associated with seagrass beds (that we discuss on page 18, lines 16-21 of the revised manuscript). However, the amount of total volume loss at these study sites is substantial. To put this in perspective, our results indicate that seafloor volume has decreased in the Upper Florida Keys study site by 14.6 (lower bound) to 37.9 (upper bound) million cubic meters. One million cubic meters is approximately the same volume as the Empire State Building. So, the amount of seafloor volume lost in this area is equivalent to approximately 14 to 37 Empire State Building's worth of material volume. There is no evidence from the numerous other geological, ecological, or geophysical studies throughout the Florida Keys for redistribution and deposition of this amount of seafloor material in the shallow habitats that lie between the outer reef tract and the shoreline of the Florida Keys.

Concerning the Florida Keys, curiously nothing is said in this paper about the dominant modes of platform change and about Keys' landward migration. This suggests that the general context that allows interpreting correctly the results is not presented and considered when analysing the results.

We have included a brief summary of Holocene reef formation and platform change in the Florida Keys to help develop the context for the analysis described in section 2.4 (Lower Florida Keys – volume to Pleistocene Bedrock), see page 25, lines 5-23 of revised manuscript. The time period of our elevation change analysis in the Florida Keys focuses on changes over the past 64 to 68 years. We feel that a broader discussion of platform evolution and change that occurs over much longer time scales than the processes accounting for much of the change we observe (discussed in manuscript) is well beyond the scope of our paper. Additionally, all of our data were corrected for sea level rise that accounts for subsidence, etc.

The results obtained in Saint Thomas, as shown by Map a page 31 mainly exhibit stability to limited elevation loss, if we consider grey and yellow areas. When we see this map, we are not convinced that elevation losses prevail, especially if we consider the error range. The same observation can be made when considering map c page 31 showing the situation of Buck Island (blue and yellow area are extensive).

We have adjusted the color schemes in all of our map figures (5, 6 and 7) to better illustrate gains and losses. The figures in the original manuscript were unevenly toned such that colors showing elevation gains overwhelmed colors showing elevation losses. We have also moved [now] Table 9 from the supplemental to the main manuscript. This table provides detailed elevation gain and loss data from each habitat type.

Reviewer 3

Overall, I am impressed by this paper and think that it is an interesting attempt to elevate monitoring to something more than “counting corals”. However, I am concerned that the likely variability in sources of substrate change were probably much more different from site to site than has been characterized. I could be wrong, but I suspect that bioerosion is less of a factor than is represented here. . . and is more likely declining at most Caribbean sites. While there is an effort to address site-to-site variability, I am not convinced that the relative roles of simple bioerosion, large-scale rugosity loss and export by storms have been adequately considered. I would like to see this paper appear in print, if only for the valuable data set. However, I am concerned that the explanations of the measured patterns is a bit oversimplified and relies too much on the mechanisms proposed. I, therefore, provide some over-arching thoughts below in the hope that the authors can perhaps think a bit more about other possible explanations for the patterns they observed. Accordingly, I make a few general observations below that will hopefully be useful.

We have clarified that the primary intent for this paper was not to focus on a detailed analysis of the processes causing elevation change, rather to focus on introducing this type of monitoring approach to the coral reef scientific community as the first application of seafloor elevation change methods to whole coral reef ecosystems, to demonstrate the value of this approach, and to report the substantial regional-scale net change in seafloor elevation that has occurred over the past several decades and has gone undocumented until now. We have added an expanded explanation of the aim and scope of our study to the introduction on page 3, line 11 to beginning of page 4. We have also emphasized that our methods do not attribute change to cause in an expanded section of our discussion, page 19, line 24 to page 21, line 2. In this section we have clarified that discussion of mechanisms of substrate change was an exercise to demonstrate the magnitude of net erosion that we measured by elevation change relative to individual processes for which process rate estimates were available including bioerosion among others. We also included a statement in this section clarifying that these comparisons demonstrate of how these regional scale elevation change analyses might be used to help attribute change to cause by way of identifying and quantifying changes that have been unaccounted for by known process rates.

Comments:

Like Reviewer 1, I am not well versed in the GIS and data transformation methods utilized in this study. However, I am familiar with the vagaries of older hydrographic surveys. On the latter front, I am willing to accept their characterizations of (the direction of?) change in substrate level as the differences between sites are probably sufficient to overcome any stated errors. However, in my experience, the notes on smooth sheets leave us with a need to make defensible assumptions about a) the reliability of substrate characterization (and its stability) and b) how processes that potentially influence elevation change might differ from site to site. I have limited my comments to the latter, based on areas in the manuscript where I have experience in either the specific habitats or the processes that might contribute to the patterns described.

Before I start, I do have one comment on style. I am not qualified to comment on the statistics of the methods or the assumptions made in the GIS transformations and map algebra. Nevertheless, a more reader-friendly explanation on that front would make the paper more accessible to a broader audience. The paper in its present form is a wealth of information on methods for those inclined to apply them to other sites. However, those people are probably going to be less well informed on the evolution of carbonate substrates. Conversely, those with intimate understanding of carbonate cycling are going to be unable to tie their knowledge to the details of the methodology used here. I am in that latter group and would suggest that the minutiae of the transformations and GIS tools could be better placed in the Supplemental Materials.

We have rewritten the methods section so that a broader audience can more easily follow along and have made significant other changes including:

- 1) We have created and included a flow diagram (Figure 1 in revised manuscript) that depicts the core processing steps in our methods.
- 2) We have moved the technical data processing steps to a supplementary methods section.
- 3) We included Section 2.2 (page 7, lines 15-31) on the methods we used for preliminary inspection of historical data sets during the selection process, including an example figure of that process (Figure 2).
- 4) We included more detailed discussion on developing the elevation-change surface models used in our study and an example figure (Figure 3) to further illustrate the process. We have also included photographs from visual inspection of our study sites as supporting evidence for our discussion (Figures 8 and 9).
- 5) We have included more detail on the very rigorous data and error evaluation analyses that we performed including a detailed discussion of data resolution and allowances for historical and modern data (page 6, line 10 – page 7, line 13).
- 6) We also included methods and results for pavement analyses we performed to determine validity of comparing historical and modern data sets (page 13, one 25 – page 14, line 11) prior to beginning elevation-change analyses, and a figure of results from this analysis (Figure 4).
- 7) We have also modified our discussion of error calculations to better clarify these methods page 11, line 15 – page 15, line 20.
- 8) We have moved supplementary Tables S1, S2 and S3 that describe details regarding the data sources, data conversions and study periods for each study site to the main paper, now Tables 2, 3 and 4 in revised manuscript, to help further clarify our methods.

The following are my general thoughts based on elements of carbonate cycling that could lead to conclusions other than those drawn here. While I am willing to accept the numerical changes in substrate elevation, I am somewhat less comfortable with assumptions about the degree to which they are related to bioerosion and the ensuing removal of sediment.

Bioerosion versus structural reorganization – In the discussions, there is an apparent conflation of bioerosion and spatial heterogeneity. The paper by Alvarez-Fillip et al. (1990) that is cited to document the role of

increased bioerosion focused on the loss in architectural complexity (aka rugosity) and its causes – not bioerosion. In the paper, they attributed the initial reduction in reef rugosity to the loss of acroporids and the second decline in rugosity to a loss of massive species following bleaching. It seems reasonable to assume that an increase in susceptible substrate could increase bioerosion. However, Alvarez-Fillip et al. focused on the loss of rugosity which, in the case of *A. palmata*, is more easily explained by physical toppling/breakage and incorporation of fragments into a broad, cemented pavement.

The Alvarez-Filip et al. (1990) reference should have been listed earlier in the sentence to which the reviewer is referring. We thank the reviewer for catching this mistake. On page 1, line 30 through page 2, lines 1-3 of the original manuscript, the sentence reads:

“Local and global, natural and human-induced stressors have caused the loss of reef-building organisms and reef structure, a decrease in biodiversity, a transition to algal-dominated communities (Pandolfi et al., 2003), and an increase of bioerosion (Alvarez-Filip et al., 2009), placing coral reefs around the world in a state of rapid decline (Madin and Madin, 2015).”

The Alvarez-Filip reference should have been placed after the statement “...have caused the loss of reef-building organisms and reef structure...”. The reference that was intended to follow the statement “...and an increase in bioerosion...” should have been Enochs et al. (2015), see reference list in manuscript. The Enochs reference discusses experimental and modeling results showing that ocean acidification increases bioerosion of coral by the boring sponge *Pione lampa*. We have corrected this mistake and clarified in this sentence that we are referring specifically to some species of boring and endolithic bioeroders. We have also include the following references as other examples (see page 1, line 25 to page 2, line 5):

Wisshak M, Schönberg CHL, Form A, Freiwald A. 2013. Effects of ocean acidification and global warming on reef bioerosion – lessons from a clonoid sponge. *Aquat Biol.* 19(2):111–127. <http://dx.doi.org/10.3354/ab00527>

Wisshak M, Schönberg CHL, Form A, Freiwald A. 2012. Ocean acidification accelerates reef bioerosion. *PLoS ONE.* 7:e45124. <http://dx.doi.org/10.1371/journal.pone.0045124>

Tribollet A, Godinot C, Atkinson M, Langdon C. 2009. Effects of elevated pCO₂ on dissolution of coral carbonates by microbial euendoliths. *Global Biogeochem Cycles.* 23(3):1–7. [http:// dx.doi.org/10.1029/2008GB003286](http://dx.doi.org/10.1029/2008GB003286)

Reyes-Nivia C, Diaz-Pulido G, Kline D, Hoegh-Guldberg O, Dove S. 2013. Ocean acidification and warming scenarios increase microbioerosion of coral skeletons. *Glob Change Biol.* 19(6):1919–1929. <http://dx.doi.org/10.1111/gcb.12158>

DeCarlo T., Cohen, A., Barkley, H., Cobban, Q., Young, C., Shamberger, K., Brainard, R., and Golbuu, Y. 2015. Coral macrobioerosion is accelerated by ocean acidification and nutrient. *Geology* 43, 7-10, doi:10.1130/G36147.1

The interval of measured elevation changes included the loss of *A. palmata*. It, therefore, seems likely that this could have played a greater role than the removal of bioeroded sediment in the changes described in the manuscript. Alvarez et al also pointed out that the loss of *Diadema* logically reduced bioerosion despite the greater availability of “bioerodable substrate”. Likewise, in many (most?) Caribbean and western Atlantic sites, parrotfish populations have been decimated, further reducing the potential for bioerosion by grazers. The remaining option is infaunal bioerosion by sponges, worms, etc. However, unless there is a very significant increase in organic availability, the likelihood of that being significant seems unlikely.

We agree that loss of *A. palmata* and other framework building species likely contributed to elevation loss at these study sites, and we address this issue in section 3.2 beginning on page 16, line 18. We have also added more detailed discussion of the effect of coral toppling without bioerosion on elevation and volume changes (page 10, lines 10-27), as well as information on declines in grazing bioeroders for these study sites in Table 1 and discussion on page 4 beginning on line 20. We have expanded our discussion of the relative roles of bioerosion versus physically toppling of corals and how these processes might affect results (page 17, line 10 to beginning of page 18). We have also shown by comparison to studies that consider rates of bioerosion, that bioerosion alone cannot account for the elevation and volume losses that we observed, page 21, line 31 to page 22, line 25. We note that much of the erosion we observed at our study sites is likely attributed to causes other than export of bioeroded sediments, page 22, lines 24-25.

It is interesting that at one of their sites (Buck Island), Bill Gladfelter proposed two threats to reef building in a 1977 report to the Park Service: 1) the loss of carbonate production if WBD increased, and 2) the possibility that protection of parrotfish might significantly increase bioerosion to the point where it could overwhelm even productive reefs. This would suggest that increased bioerosion by grazing fish could lead to detrimental increase in bioerosion. In the latter scenario, increased grazing becomes a problem only in protected areas where grazing fish have increased (like the FKMS, one of the described sites where increased bioerosion might be a reasonable culprit). Elsewhere in the Caribbean, parrotfish populations have been decimated. In combination with the loss of the major grazing urchin, a wholesale increase in bioerosion capacity seems unlikely. Lost calcification ability would decrease accretion, but does not seem like a driver of net erosion unless bioerosion increases – a pattern that has not been documented at all sites.

We agree that losses and gains of grazing fish will directly impact rates of bioerosion by those species. We have clarified in our discussion that there are a number of different types of bioeroder species including grazing fish as well as sponges, bivalves, microendoliths, etc. We have noted the potential impact of increases or decreases in grazing fish on rates of bioerosion; and we clarified that recent work indicates that elevated pCO₂ and ocean

acidification accelerates bioerosion by endoliths and other boring bioeroders. See pages 17, line 27 to page 18, line 5. While we point to bioerosion as one of many contributors to erosion in these systems, we agree (and show by comparison in our discussion) that the contribution is small relative to the net changes we measured.

So, that leaves us with export. As the paper points out, good data on export are rare. On page 2, Moses (2009) is cited for measuring sediment export from reefs, but I could find no measurements in that paper. Kench and McLean provide an estimate of transport potential through HOA in Indian Ocean atolls. However, the results are based on theoretical calculations and there is no effort to tie sediment to specific sources (e.g., bioeroded sediment, beaches, lagoons) or sinks (loss to lagoons vs export from the platform).

The reviewer is mistaken regarding the Moses (2009) reference. Moses (2009) is cited with respect to regional-scale chemical erosion measurements of carbonates (page 2, lines 23-24). In a sentence after that (beginning on line 24), Morgan and Kench (2014) and Kench and McLean (2004) are cited in a sentence that reads “Very few studies have quantified sediment transport and export on reef systems”. We note again here that many of our references in the paper have typos in them from our End Note conversion that we did not catch prior to submission. For example, many were abbreviated (e.g. Morgan and Kench 2014 got shortened to Morgan 2014, and Kench and McLean 2004 got shortened to Kench 2004), and others reverted back to numbers (as was the case in Supplementary Table 1 in which the source references reverted back to numbers). We have corrected all of these in the revised paper.

Morgan and Kench (2014) is one of the few studies that estimated sediment flux and off-reef sediment export from direct point measurements using arrays of bi-directional sediment traps for an atoll reef (Vabbinfaru reef, North Male' Atoll) in the Maldives. They showed high off-reef export rates for both gravel and sand (annual export estimated at over 120 metric tons per year), as well as high sediment flux rates even during non-storm conditions.

Kench and McLean (2004) estimated transport potential from current meter and tidal gauges located in the HOAs, but also measured sediment fluxes in HOA's from sediment traps ranging from approximately 2kg to 268 kg per day. Based on daily rates of sediment flux, they estimate that from 44 to 223 metric tons per year of sediment may be transported by HOA's.

We have included additional references to sediment export studies by Hubbard in this section (page 2, lines 24-25). We have also expanded our discussion of sediment export including more detailed discussion of results from previous studies (including Hubbard et al., 1981; Hubbard, 1986; Hubbard et al., 1990; Hubbard, 1992) as well as supporting evidence for our results from sediment resuspension and transport studies by Ogston, Presto, Storlazzi, and Fletcher), see page 23 line 16 to page 24, line 14). Results from these studies support our suggestion that physical erosion and export of sediments could account for much of the volume loss we observed at our study sites (page 12, line 25-28).

What is, therefore, critically important is a reliable estimate of export inas- much as volume must be exported from the system to trigger system-wide elevation loss. . . bioerosion just converts carbonate from solid substrate to sediment. In the lat- ter case, we must remember that sediment has a much lower bulk density than solid carbonate substrate. Thus, increased bioerosion without export would reduce the vol- ume of solid substrate but would turn this into a sediment pile with something akin to twice the net volume. Thus, increased bioerosion without export would result in sub- strate elevation; not lowering. A scenario based solely on increased bioerosion seems inadequate to explain the measured patterns.

We agree with the reviewer, and make the case in our results and discussion that the volume loss we observe over the large scale of our study sites is an indication of export of materials from these systems. We do not suggest that any scenarios based solely on increased bioerosion could account for the volume losses we observed. We reworded the sentence on page 22, line 23-25 to clarify that export of bioeroded sediment cannot fully account for the erosion we observed at our study sites. As indicated, we have greatly expanded our discussion on physical erosion and export of sediments as a likely cause for much of the erosion we have observed.

Unfortunately, there has only been a few careful measurements of sediment export in the context of a reef- wide budget. Perry and various co-authors use our ratio (Export ~ 50% of total bioerosion) from the north coast of St. Croix to characterize this in every one of their budgets. It is naïve to think that all reefs in all oceans have the same energy regime (the driver of export) – or that changes in energy regime is offset by proportional shifts in bioerosion to maintain the 50% value that is used throughout. With increasing storminess, sediment export looms as the single largest unquantified variable. Therefore, export can only get more significant in the budgeting attempted in this paper.

Again, we agree with the reviewer. Note in our discussion that we suggest that much of the volume loss we observe in these regions may be attributed to physical transport and export of sediments, and that export has been largely unaccounted for in previous studies (page 22, lines 23-26). We also note that the much greater seafloor elevation and volume losses observed over shorter time periods at the Maui study site could be caused by higher sediment export rates due to a combination of higher wave energy and physical erosion as well as a narrow shelf surrounding the island (page 19, lines 6-11). We have also added discussion of sediment flux studies that support this concept (page 23, lines 6-16).

In section 3.2, the paper acknowledges the difference between bioerosion and changes in structural complexity. How good the conclusion will be is going to depend on how well one can distinguish between the two as potential drivers of elevation change. The conclusions presented here seem to suggest 1) an ability to reliably distinguish be- tween the two mechanisms and 2) an overwhelming importance of simple bioerosion over combined changes in export and reduced structural complexity following the loss of biological constructors.

We have clarified and emphasized that our analyses do not attribute change to cause. We make no claims to be able to distinguish between bioerosion and changes in structural complexity. We have provided photographic evidence (Figure 8 in revised manuscript) to illustrate how loss of structural complexity can differ from the result of bioerosion, and as evidence that physical degradation (toppling of corals) has occurred at the BI study site, consistent with observations of elevation loss. We feel that our expanded discussion now emphasizes the role of changes in export and reduced structural complexity as likely causes for much of the erosion we observed at these study sites (page 22, line 28 to page 24, line 15).

Anthropogenic drivers of change - Using population as a proxy for anthropogenic impact seems overly simplified. Numerous recent papers have shown that some of the greatest reef losses occur due to warming/acidification at great distances from any recognizable urban stressors. I can't find the specific papers, but there has been quite a bit of discussion on the NOAA listserv about papers that show just this. While I am not in the midst of the debate over local versus global drivers of change and their implications for management, this proxy seems a bit simplistic.

We have removed the statements that we use population as a proxy for anthropogenic impact, and instead we simply state that population has doubled and local anthropogenic impacts have increased at each study site (page 5, lines 19-22). We have moved the Table with population statistics from the supplemental to the main paper (Table 2), and we also include a table and discussion on declines in coral cover and other indicator species (Table 1, page 4, line 20 to page 5, line 5) as evidence for anthropogenic impacts.

We cited Perry's (2015) work showing that reef systems in the Indian Ocean that are geographically isolated and lack human influence show heavy impact from bleaching events, but are able to recover very rapidly (see discussion on page 24, lines 23-31) and show very high accretion rates. We note that Maui is geographically isolated but shows very large erosion rates suggesting that it has not been able to recover from reef loss, possibly due to the fact that it is not isolated from a large human population. We also point out more than one case where lower losses of elevation and volume coincide with areas further removed from large population centers or associated with natural refuge zones (same section).

On a more specific point, the manuscript discusses the idea of proximity to anthropogenic areas to explain the positive elevation change in the lower Keys. Couldn't this also be due to separation from the inimical cold bank water allowing for higher calcification rates? In this vein, limited core data from the Keys seem to suggest that the "demise" of the reef tract likely started 4-5,000 years ago as Florida Bay flooded, triggering inimical (cold) water export onto the reefs. In contrast, the reefs around Buck Island enjoyed continuous building throughout this period as there was no similar source of stress.

The reviewer misunderstood this discussion now located on page 18, lines 16 – 21:

“Mean total elevation loss was lowest at the UFK study site. However, mean elevation losses decreased from upper (-0.4 m) to central (-0.3 m) sub-regions of the UFK, and mean elevation increased slightly in the lower sub-region (0.1 m) primarily associated with seagrass habitat (Fig. 1a, b). Notably, the lower sub-region is further away from high-density population areas north of the study site and near an area of the middle Florida Keys identified as a possible refuge from ocean acidification due to seagrass productivity (Manzello et al., 2012).”

The area that showed the elevation increase was in the lower sub-region of the Upper Florida Keys (not in the Lower Florida Keys), see Figure 5a in the revised manuscript. The mean elevation change in the Lower Florida Keys was -0.3 m (see Table 8 in revised manuscript), and was similar to the elevation loss we observed in the central sub-region of the Upper Florida Keys. These data would suggest that the inimical waters could be less likely to have had an impact on this sub-region of the Upper Florida Keys.

All of this would suggest that these two areas have had very different exposures to natural stresses; this would presumably make for very different susceptibilities in more recent times when increasing anthropogenic stress is set up as the main driver. It may also be noteworthy that the sediment thicknesses in these two areas are different and there is evidence that sediment retention around Buck Island (much higher wave energy and susceptibility to both storm damage and sediment export) may tend to be less than is the case in the Keys. If the latter is true, then changes in substrate elevation might be sediment export in one place, bioerosion in another and wholesale loss of rugosity in all.

Interestingly, our volume calculations showed the lowest ‘maximum net volume’ loss (Table 8, column 10 in revised manuscript) and ‘mean elevation’ loss (Table 8, column 3 in revised manuscript) at Buck Island, suggesting that sediment/material retention was greater at Buck Island over the study period than in the Florida Keys. We suggest that this could be due to loss of rugosity (large framework building coral) but less export of materials at Buck Island and have expanded our discussion of that beginning on page 17, line 10. We also added photos from the Buck Island study site supporting our observations of rugosity loss and the potential implications for materials transport in this section.

I assume that the substrate type and sediment thickness was not consistently noted in older surveys. Given the points above, this could be an important driver of how quickly substrate elevation might change in one place versus another. The wholesale loss of architecturally complex acroporids and the subsequent reduction of these to pavement could be construed as “degradation of framework-building corals” as could bioerosion. Which was the main agent in each case?

Unfortunately, substrate type and sediment thickness were not consistently noted in the older surveys.

Reviewer 3 – additional comment

As I initially said, I think this is a good study - for exactly the same reasons the readers intended. I am satisfied with the revision suggestions but strongly encourage the authors to make sure that the reader understands that the main goal is to focus on the magnitude of change with the caveat that attributing mechanisms is much less well constrained. In this vein, I suggest that the authors take an opportunity to perhaps comment on where we have big gaps in our knowledge that hamper such attributions and why at least a semi-quantitative understanding of the relative relationships between carbonate addition and removal is important to our understanding of the changing dynamic between accretion/erosion and SL rise. The non-linear relationship between water depth across the reef and wave energy passing by has been elegantly demonstrated by many careful instrumental studies. This study addresses ways to quantify the first half of that relationship and, therefore, has considerable value when we move on from coral loss to longer-term physical and social impacts - whether in Miami or some small atoll in the Indo-Pacific region.

We expanded the first section of our discussion (page 19, line 24 to page 21, line 2) to comment on some of the key gaps and issues that make attribution of physical change to cause difficult in these systems, and the benefits from performing comprehensive elevation-change analyses. We have also now included a Conclusions section (page 26, beginning on line 23) that discusses the potential value of elevation change analyses for moving the field of science toward better establishing links among contemporary processes causing coral reef ecosystem degradation, long-term changes in the physical structure of the environment, and future implications for physical and societal impacts. We also include discussion of the key limitations of elevation change analyses, and summarize the key findings from our study.

Reviewer 4

The paper by Yates et al. analyses bathymetric data to quantify seafloor elevation changes in coral reef regions. As highlighted by reviewers 1 and 3, the dataset presented in the manuscript is especially impressive (number of sites considered, extent of the area considered). The results will be useful for coastal geomorphologists and managers concerned with the sustainability of coral reef environments and the related ecosystem services. Despite the recommendation of reviewer 2, I think that the paper should be published after major revisions, to ensure that the amount of data analyzed in this work receives the attention it deserves.

Three previous reviews have extensively discussed the paper: overall, reviewers (1) have concerns regarding the ability of the method to retrieve seafloor elevation changes at the required accuracy; (2) made comments on the form of the paper; (3) and the interpretation of the results. The authors have already provided responses to several comments of the reviewers, and intend to implement corrections to their paper, which I

think are reasonable. I would suggest that these major revisions are implemented, considering the following points:

- All reviewers agree that the paper should separate more clearly what is the overall approach (comparing bathymetric data) from the technical details of the GIS procedure used to produce this data. The authors have prepared a figure as part of their response to reviewer 1 to address this comment. However, I think that the figure remains too technical (e.g., use of the TIN surface wording), and I would support producing the detailed GIS procedure in an annex to the paper. Overall, I agree with previous reviews, who suggested that the authors should consider that their results may have a large impact beyond specialists of coastal bathymetric surveys, so that ideally, they should try to separate the main messages from the technical implementation details.

We have rewritten the methods section taking into account the suggestions by all of the reviewers, and we have included the more detailed (GIS) steps in a methods supplementary section. We included a modified flow diagram (Figure 1 in revised manuscript) showing our approach to describe the process in more general terms. See also responses to reviewers 1 and 3.

While the comparison of historical bathymetric sounding with contemporary LiDAR is quite widespread in coastal geomorphology (as reminded by the authors, see AC2 – pages C6-C7), there is always the suspicion that the two techniques induce errors, as highlighted by reviewers 1 and 2. Such errors can arise because the techniques have not the same purpose and therefore don't necessarily capture the same proxies (e.g., highest seafloor elevation features for navigation applications vs average seafloor elevation feature for bathymetry data in support to coastal hydrographic modelling). The techniques also have different accuracy/precision (as discussed already), or because of time-sampling issues (as commented by reviewer 2). Overall, I think that the authors make a fair assessment of these errors: in the response of the authors to this comment of reviewer 2 (AC2 pages C8), information regarding the vertical resolution of the techniques is provided, while the precision issues are given in Table 4 in the original manuscript. To complete this assessment, I would suggest to provide more information on the planimetric resolution, and the vertical accuracy of the techniques in the core of the article. This includes details regarding the definition of a common reference, which incorporates sea-level rise constructions in a way, which is not completely clear to me based on the original manuscript, page 4 lines 10 and following. Nevertheless, I am confident this does not affect the results of the authors, as the RMSE in vertical datum adjustment is probably much larger than the RMSE due to uncertainties in relative sea-level changes for the sites of interest (table 4).

We have included a statement of caution that not all historical and modern data sets are appropriate for elevation change analyses and indicated considerations that must be made on page 5, lines 24-29. We added discussion and quantification of the historical sounding point densities for each study (page 8, lines 26-30). We point out the

potential limitation of planimetric resolution on page 15, lines 14-17. We included a section on preliminary inspection of historical data sets for horizontal alignment prior to data analysis, and provided an example figure of that process (Figure 2). We also included our pavement analysis and results (Section 2.12, page 13, line 25 to page 14, line 11) as further evidence for the accuracy of these data and the validity of comparing these data sets (with a strong caution that pavement cannot be appropriately used as a control, but can provide supporting information for proper error analyses). We provided very basic definitions of horizontal and vertical references (datums) for these data sets and the need to adjust data so that compared data sets are aligned to the same reference points (Section 2.4, page 8, lines 13-20). We reworded the section on sea level rise correction (Section 2.3, page 8, beginning on line 1) to more clearly explain these corrections. We added information on the range of sea level correction values and showed that the potential error from these corrections was insignificant relative to other sources of error, and we, therefore, excluded it from our RMSE calculations (page 8, lines 8-11). We moved information on the data and sources we used for our sea level rise corrections from the supplemental section to the main paper to help clarify our sea level rise adjustments (Table 4 in revised manuscript).

Regarding the interpretation of the results: besides the aspects discussed with reviewer 1 and 2, I think that reviewer 3 provides a very clear line for improving the discussion section, and I hope that the authors will build on it in a future version of the article.

We have greatly expanded our discussion section based on comments from reviewers 1, 2 and 3, see responses to those reviewers.

Finally, I think that a “conclusion” section is needed.

We have included a conclusions section that points out the benefits and limitations of comprehensive elevation change analyses, and summarizes the key findings of our study.

I hope these comments are useful.

Divergence of seafloor elevation and sea level rise in coral reef ecosystems

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Abstract. Coral reefs serve as natural barriers that protect adjacent shorelines from coastal hazards such as storms, waves and erosion. Projections indicate global degradation of coral reefs due to anthropogenic impacts and climate change will cause a transition to net erosion by mid-century. Here, we provide a comprehensive assessment of the combined effect of all of the processes affecting seafloor accretion and erosion by measuring changes in seafloor elevation and volume for 5 coral reef ecosystems in the Atlantic, Pacific and Caribbean over the last several decades. Regional-scale mean elevation and volume losses were observed at all 5 study sites and in 77% of the 60 individual habitats that we examined across all study sites. Mean seafloor elevation losses for whole coral reef ecosystems in our study ranged from -0.09 m to -0.8 m, corresponding to net volume losses ranging from 3.4 to 80.5 Mm³ for all study sites. Erosion of both coral-dominated substrate and non-coral substrate suggests that the current rate of carbonate production is no longer sufficient to support net accretion of coral reefs or adjacent habitats. We show that regional-scale loss of seafloor elevation and volume has accelerated the rate of relative sea level rise in these regions. Current water depths have increased to levels not predicted until near the year 2100, placing these ecosystems and nearby communities at elevated and accelerating risk to coastal hazards. Our results set a new baseline for projecting future impacts to coastal communities resulting from degradation of coral reef systems and associated losses of natural and socio-economic resources.

1 Introduction

Coral reef ecosystems develop over thousands of years as organisms build skeletons of calcium carbonate minerals that form complex 3-dimensional structures, and keep pace with rising sea level through continued growth and accretion of carbonate sediments. These ecosystems support up to 25% of fisheries in tropical regions and developing nations (Garcia and Moreno, 2003), and economic and recreational services for more than 100 countries (Burke et al., 2011). Reef framework and shallow, non-coral-dominated habitats serve as natural barriers that protect shoreline ecosystems and coastal communities by reducing hazards from waves, storm surges and tsunamis for more than 200 million people around the world (Sheppard et

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al., 2005; Ferrario et al., 2014). Local and global, natural and human-induced stressors have caused the loss of reef-building organisms and reef structure (Alvarez-Filip et al., 2009), a decrease in biodiversity, a transition to algal-dominated communities (Pandolfi et al., 2003), and an increase in bioerosion by some species of sponges and other boring and endolithic bioeroders (Tribollet et al., 2009; Wisshak et al., 2012; Reyes-Nivia et al., 2013; Wisshak et al., 2013; Decarlo et al., 2015; Enochs et al., 2015) placing coral reefs around the world in a state of rapid decline (Madin and Madin, 2015).

Coral reef degradation and the causes have been well documented since the 1970's (Gardner et al., 2003) when regional-scale species compositions that remained stable throughout the Pleistocene and Holocene began changing (Aronson et al., 2002). Most reef degradation has been attributed primarily to impacts of coastal development, overfishing, pollution, nutrient enrichment, coral bleaching and disease (Glynn, 1984; Greenstein et al., 1998). Abundance of reef-building corals has decreased as much as 72% since 1968 on Pacific reefs and as much as 50% since 1970 on many Caribbean reefs (Gardner et al., 2003; Bruno and Selig, 2007; Jackson et al., 2014). Carbonate production rates have decreased to below historical values on Caribbean reefs and carbonate-budget models indicate that some are already experiencing net erosion (Perry et al., 2013; Enochs et al., 2015). Projections indicate up to 66% of coral reefs worldwide will continue to degrade in the next few decades due to ocean warming and acidification from unprecedented rates of global climate change (Frieler et al., 2013) that may cause reef erosion to exceed accretion (Hoegh-Guldberg et al., 2007). Ancient reef crises linked to global climate change during the past 500 million years are marked in the geologic record by major decreases in carbonate accretion and reef volume (Kiessling and Simpson, 2011).

Numerous studies have modelled reef- to regional-scale accretion and erosion on coral reefs based solely on carbonate budgets some of which account for rates of bioerosion (eg., Stearn et al., 1977; Brock et al., 2006b; Moses et al., 2009; Kennedy et al., 2013; Leon and Woodroffe, 2013; Perry et al., 2013; Perry et al., 2014; Enochs et al., 2015; Perry et al., 2015). Recent studies have also measured regional-scale chemical erosion of carbonates due to dissolution caused by ocean acidification (Brock et al., 2006b; Moses et al., 2009; Muehllehner et al., 2016). Very few studies have quantified sediment transport and export on reef systems (Hubbard, 1986, 1992; Hubbard et al. 1981, 1990; Kench and McLean, 2004; Morgan and Kench, 2014). Studies such as these are essential for attributing ecosystem change to cause, setting target levels for restoring and maintaining healthy reefs (Kennedy et al., 2013) and for measuring and predicting reef degradation due to these specific processes. However, no prior studies provide a comprehensive assessment of the combined effect of all of the processes affecting seafloor accretion and erosion in coral reef ecosystems, including for example, physical erosion; redistribution, import or export of seafloor sediments; compaction; direct human alterations to the seafloor; carbonate production; bioerosion; and chemical erosion. Such comprehensive assessments are essential for accurately quantifying and monitoring whole system accretion and erosion, identifying resilient and vulnerable seafloor habitats, and for identifying gaps in accounting for the individual processes causing ecosystem change. Additionally, development of hydrodynamic and other numerical models used to assess and predict the impact of reef degradation on the vulnerability of coastal communities

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to hazards caused by storms, waves, sea level rise and erosion, have been limited by lack of comprehensive assessments of change in the complex seafloor structure of coral reef ecosystems.

Recent advances in high-resolution bathymetric mapping capabilities such as Light Detection and Ranging (LiDAR) systems (Brock et al., 2002; Crane et al., 2004) provide the ability to map coral reef ecosystems with the spatial resolution needed to accurately measure elevation over their highly variable and complex topography. Combined analysis of high-resolution digital elevation models derived from LiDAR data and appropriate historical bathymetric data can provide comprehensive assessments of seafloor elevation and volume change to determine regional-scale and habitat-scale accretion and erosion in coral reef ecosystems. These types of regional-scale, elevation-change analyses can be used by numerical modellers to improve our ability to predict potential impacts to coastal communities due to degradation of coral reef ecosystems.

The aim of our study was to quantify regional-scale changes in seafloor elevation in coral reef ecosystems in the Atlantic (Upper and Lower Florida Keys), Caribbean (St. Thomas and Buck Island, U.S. Virgin Islands), and Pacific (Maui, Hawaii) including both coral-dominated habitats and adjacent, non-coral dominated habitats. Our study is based on the premise that elevation-change analysis measures the net result of all of the constructive processes that cause accretion (or increases in seafloor elevation) and the destructive processes that cause erosion (or decreases in seafloor elevation) on whole reef systems. This includes processes that have been broadly studied (e.g., carbonate production, biological erosion, chemical erosion, etc.), as well as processes that have not been well characterized (for example physical erosion and export). While this method does not attribute change to cause, it does provide a measure of the net result of all impacts (natural or anthropogenic) to seafloor structure in these ecosystems over the time periods studied. Furthermore, combining results from this method with habitat data helps identify potentially vulnerable and resilient habitats and provides some insight into relative contributions of broad scale processes that cause accretion, erosion, sediment redistribution and export. We used historical bathymetric data sets from the 1930's to 1980's and contemporary LiDAR-derived digital elevation models (DEMs) from the late 1990's to 2000's to calculate changes in seafloor elevation for each study site over the past few decades. We then created elevation-difference models from which we calculated corresponding changes in seafloor volume for whole study sites and for habitat types within each site. This type of elevation change analysis (using comparisons between historical and modern elevation data sets) has traditionally been used by coastal engineers to monitor seafloor changes such as sediment accretion and erosion, and migration of shipping channels, sand bars, mud banks and other seafloor features in coastal environments (Byrnes et al., 2002; Taylor and Purkis, 2012; Byrnes et al., 2013). To our knowledge, this study is the first to apply these methods to coral reef ecosystems. Here, we introduce the application of these seafloor elevation-change methods to whole coral reef ecosystems. We discuss elevation- and volume-change results in general context with known processes occurring in these systems to demonstrate the magnitude of change we observed and the value of this approach for regional-scale research and monitoring of impacts to reef ecosystems. Additionally, we report

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substantial regional-scale net change in seafloor elevation that has occurred over the past several decades and its implications for sea level rise and risk from coastal hazards.

2 Methods and error analyses

Our study examined changes in seafloor elevation within 5 regions characterized by extensive coral reef ecosystems that included reef flats as well as reef crest and slope habitats, adjacent (non-coral dominated) habitats such as seagrass beds, sand bottom, and hard bottom communities, and (in some cases) deeper water habitats. We chose to perform our analyses at the coral reef ecosystem scale because accretion in non-coral dominated habitats within these ecosystems, as well as off shore habitats (and beaches which are excluded from our study), are supported by sand/sediment production from the breakdown of carbonate produced by corals and other calcifying reef organisms. Few studies have quantified the effect of reef degradation on accretion and erosion of non-coral dominated habitats at the coral reef ecosystem scale.

Our Florida Keys study site included outer reef track and surrounding habitats of the Upper Florida Keys (UFK) and Lower Florida Keys (LFK), and examined changes in elevation from 1934/1935 to 2002. Our St. Thomas, U.S. Virgin Islands study site (STT) included the entire southern coastline of the island including habitat out to 5 km offshore and examined changes in elevation from 1966/1973 to 2014. Our Buck Island study site (BI) is an uninhabited location that included an extensive area east of the island and to a depth of 37 m, and examined changes in elevation from 1981/1982 to 2014. Our Maui, Hawaii study site included the coastal region surrounding the entire island to a depth of 20 m and examined changes in elevation from 1961/1965 to 1999. The size of each study area is provided in Table 1.

Long term monitoring data show that each of these coral reef ecosystems have experienced losses in live coral cover as well as changes in abundance of macroalgae and grazing reef bioeroders over the past couple of decades. Jackson et al. (2014) synthesized results from 19 different studies in the Florida Keys spanning the years 1973 to 2011, and 32 different studies in the U.S. Virgin Islands spanning the years 1973 to 2011, that collected benthic cover and herbivore data. These data show that, in general, live coral cover has decreased and macroalgal cover has increased in the UFK, LFK, STT, and St. Croix (including Buck Island). *Diadema sp.* sea urchin densities have either decreased and/or remained absent at these study sites; and the biomass of parrotfish increased at in the UFK, LFK, and STT and decreased in St. Croix over these time periods (Table 1). Jackson et al. (2014) provide a detailed discussion of the major drivers of coral reef decline in the Caribbean including human population density, fishing, coastal pollution, ocean warming, invasive species, coral disease and the role of hurricanes. Sparks et al. (2015) performed benthic surveys of 10 areas along the western coast of Maui including 20 reef sites as well as shallow (1 to 4 m) and deep (6 to 13 m) sites from 1999 to 2015. Results from these surveys indicate significant decreases in coral cover at 8 coral reef sites (average decrease ~12%), significant increases at 4 sites (average increase ~4%), no significant change at 8 sites, and an average decrease of ~4% for all study sites combined during this time

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period. Macroalgal cover was monitored at 5 locations and showed substantial decreases at most sites. Parrotfish were monitored at 6 sites, showed no significant change at most sites, and significant increases at two sites located in protected areas (Table 1). Sparks et al. (2015) noted that declines in coral cover are likely due to sedimentation, land based pollution and overfishing, and that monitoring sites with stable coral cover are remote and less affected by urban and other anthropogenic factors.

The general concept of calculating the difference between corresponding modern and historical elevation data points is simple. However, the methodology used to validate and prepare data for analysis, determine error and quantify the effect of that error on results is complex. We, therefore, provide both a general discussion of the methodology (depicted in the flow-diagram in Fig. 1) for the broader scientific audience and a more technical discussion in Supplemental Methods Section 1 including step-by-step data-processing methods for those interested in pursuing similar analyses.

2.1 Selection and description of data sets

Our selection of study sites was based on the availability of historic hydrographic data that had sufficient point density and geospatial information to support meaningful comparisons with corresponding, more contemporary LiDAR data. Each of our five study sites was analysed independently over the specific time period indicated, using the oldest appropriate data available and the most recent data available. Our analysis was limited by the areal extent of available data sets. We note that there are gaps in the Florida Keys analysis where data was unavailable, including the Middle Florida Keys and near shore areas. There are also gaps in the Buck Island analysis in shallow areas surrounding the island and other areas where data was not collected. These gaps are identified in mapped results as white masked areas (Section 3.1). Full analysis of anthropogenic impact factors (e.g., urban extent, developed land, terrestrial water run-off, water quality, etc.) was beyond the scope of this study. However, our selected data sets spanned time periods during which human population approximately doubled and local anthropogenic impacts increased at each study site as well as at one uninhabited site (Table 2).

We caution that not all historical and modern data sets are appropriate for elevation change analyses. Careful consideration must be given to the original purpose of the surveys, the horizontal and vertical resolution of paired historical and modern data sets for comparison, and the horizontal resolution of data relative to the total size of the study area. We specifically chose data sets that were collected for the purpose of uniform regional-scale mapping of seafloor depth/elevation without bias toward specific seafloor features (e.g., only shallow areas, man-made features, etc.) to minimize skewing of the data point distribution. We performed multiple analyses to quantify and validate the horizontal and vertical error of the data sets (See Sections 2.11, 2.12, 2.13), as well as the effect of horizontal resolution and alignment error on our results (See Section 2.13). Coarse horizontal resolution of many historical data sets limits their use for elevation-change analyses to only large, regional-scale areas such as those addressed in this study (Section 2.13).

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We used historical hydrographic survey (H-sheet) data collected by the United States Coast and Geodetic Survey (USC&GS) or the National Ocean Service (NOS) between 1934 and 1982. These historical data included digital XYZ sounding data for water depth as well the accompanying descriptive reports and smooth sheets (final map renderings), and were downloaded from the National Oceanic and Atmospheric Administration's (NOAA) Office of Coast Survey (NOAA Office of Coast Survey). The number of H-sheets used for each study site varied from 1 to 24 depending on geographic area. All data sources and descriptions are listed in Table 3. During these surveys several methods were used to collect depth soundings by USC&GS/NOS including lead line, graduated sounding-pole and fathometer, and methodology was noted in each H-sheet descriptive report along with measurement resolution information.

In general, for the 1930's surveys, sounding poles were often used in water depths approximately less than 3 m and replaced with lead lines at greater depths. Sounding positions for 1930's data were determined by sextant triangulations using both permanent and temporary topographic reference points or triangulation stations, theodolite fixes, navigational beacons, and ship time and speed fixes (Shalowitz, 1964). Most of the surveys after 1960 were performed using a fathometer, and augmented with lead line soundings. The historical sounding data for Buck Island and Maui, collected using a fathometer, were reported to the nearest tenth of a fathom (0.18 m) for water depths less than 20 fathoms (37 m) and 11 fathoms (20 m), respectively, and to the nearest 1 fathom (1.8 m) for greater water depths. Therefore, we only used data from shallower depths than these thresholds (0.18 m resolution) at these study sites. Following field surveys, hydrographic data went through quality control protocols including adjustment for tides, removal of erroneous points, validation of track line cross-soundings, and determination of agreement with adjacent surveys to create a published smooth sheet (Shalowitz, 1964). The descriptive reports include notes from the USC&GS/NOS survey teams and details on any adjustments or changes made by reviewers. Hydrographic data used in our study that was downloaded from NOAA Office of Coast Survey had already been digitized by personnel at NOAA.

The U.S. Office of Coast Survey imparted strict standards on collection of historical hydrographic data from the 1800's to the 1950's that allowed for less error than later in the 1900's when electronic means of collecting sounding data replaced lead lining and poling (Shalowitz, 1964). For data collected by the Coast Survey from the late 1800's to 1950's, maximum allowable vertical differences at crossing data points was 0.06 m for depths less than 4.6 m, and 0.46 m for depths between 22 and 29 m (Byrnes et al., 2002). Lead line and poling vertical resolution reported for the historical data sets that we used was 0.15 m (similar to that of LiDAR), while fathometer resolution was 0.3 m. Furthermore, sounding poles were used in depths less than 3 m (where many shallow patch reefs are located). Many H-sheet descriptive reports indicated that the water was clear enough during surveys to see the bottom (which improves accuracy of the measurement). The most common error likely to occur during use of lead lines or sounding poles was overestimation of water depth due to angling of the line or pole as currents move the boat past the point of measurement. Overestimation of historical water depth would erroneously

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decrease elevation losses calculated using our methods. Therefore, it is more likely that our erosion estimates are underestimated rather than overestimated due to lead line and poling techniques. We estimated horizontal error for historical data sets of approximately 5.0 m (See Section 2.13).

5 LiDAR data sets from the USGS Coastal and Marine Geology LiDAR Program and the U.S. Army Corps of Engineers (USACE) Joint Airborne LiDAR Bathymetry Technical Center of Expertise (JALBTCX) were downloaded for each study site (Table 3. U.S. Army Corps of Engineers-JALBTCX, 1999, 2004; Brock et al., 2006a; Brock et al., 2007; Fredericks et al., 2015a, b). LiDAR-derived digital elevation models (DEMs) for Atlantic/Caribbean and Pacific sites were at horizontal spatial resolutions of 1 m and 4 m, respectively, with horizontal datums of UTM NAD83, and vertical datums of NAVD88 GEOID03 for the Atlantic, VIVD09 for the Caribbean, and MLLW for the Pacific. Vertical accuracy of LiDAR data is typically reported as the 95% RMSE (Hodgson and Bresnahan, 2004). Vertical RMSEs for the LiDAR data used in this study ranged from 0.135 m to 0.15 m as reported in the metadata accompanying the LiDAR data for each site and based on independent validation by in-water acoustic-based depth measurements at the time of collection.

2.2 Preliminary inspection of historical data sets

15 We performed visual inspection of all of the historical (H-sheet) data relative to 2016 aerial and satellite imagery with a resolution of 1 m (2016 World Imagery from ArcGIS online via ArcMap 10.2.2, source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community) to measure differences between stable coastal and geographic features following the methods of Lukas (2014) for use of historical elevation data sets. Visual inspection of map features that have not changed over the study period allows for confirmation of general horizontal alignment of the compared data sets. For example, in the Upper Florida Keys a historic bridge was surveyed in the 1930s and still existed at the time this study was performed. We overlaid the georectified 1934 H-sheet on 2016 georectified Worldview imagery in ArcMap 10.2.2 and used software-measuring tools to examine the offsets in this structure. The maximum offset of bridge boundaries between historical and modern locations was 4.8 m (Fig. 2). This offset is similar to the sum of errors reported in our horizontal error analysis in Section 2.13. We were able to identify other stable, rocky coastlines and/or man made features (such as shoreline berms) for these types of comparisons at all study sites. In offshore areas, we examined locations in the historical data where the boundaries of large patch reefs were outlined by soundings when depths were too shallow for a boat to pass over the reef causing deviations from linear transect lines. There were no significant misalignments between historical and modern boundaries for reefs that experienced minimal erosion. We performed these visual inspections for all historical (H-sheet) data from all study sites and found similar alignment agreement. Additionally, we visited select areas at all study sites to visually inspect the seafloor for erosion or accretion features that were consistent with trends identified by our analysis.

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2.3 Sea level rise correction of historical soundings

The historical sounding data was corrected for sea level rise that occurred from the time of its collection to the time of collection of the corresponding LiDAR data. We adjusted the historical soundings using NOAA relative sea level rise (RSLR) estimates to account for any differences at local tide stations caused by sea level rise, platform movement, and/or subsidence (Parker, 1992; Byrnes et al., 2013). Long-term sea level rise data (in mm per year) recorded by NOAA sea level trend stations near our study sites were used to calculate the total sea level rise at each study site by multiplying the mean rate of annual sea level rise over the study time period (mm yr^{-1}) by the number of years between historical and modern data sets. These correction values ranged from approximately 7 cm to 16 cm and were added to the historical sounding value. NOAA reports 95% confidence intervals for these data ranging from approximately ± 0.15 to ± 0.81 mm/yr. The potential error from these corrections was insignificant relative to other sources of error, and we, therefore, excluded it from our RMSE calculations. Sea level trend stations, rates and correction factors are presented in Table 4.

2.4 Conversion of historical soundings to elevations

Vertical units for the original historical sounding measurements were converted from feet and fathoms to meters by the NOAA Office of Coast Survey, but remained in their original vertical datum (reference surface of zero elevation). We determined vertical datums for the digitized soundings by reviewing the H-sheet descriptive reports and smooth sheet notes. Historical sounding data were reported relative to tidal datums of mean low water (MLW) or mean lower low water (MLLW). Comparison between historical and modern data sets required transferring sounding data to the same vertical datum as the corresponding LiDAR data so elevations could be compared relative to a common zero elevation system. NOAA also transferred horizontal datums (coordinate systems for identifying physical locations) of the digitized XYZ historical hydrographic data to North American Datum 1983 (NAD83) during the digitization process. Similarly, historical data required transformation to the same horizontal datum as corresponding LiDAR data. We performed these data transformations using publicly available software from NOAA called VDatum v 3.6 that is available along with user guides and tutorials at <https://vdatum.noaa.gov/>. Geospatial and transformation information for these conversions are provided in Table 4, and a more detailed description of the transformation procedure is provided in Supplemental Methods Section 1.1.

2.5 Extraction of modern seafloor elevation data at historical point locations

The horizontal spacing of the historical sounding points was much coarser than the resolution of the LiDAR digital elevation models (1 to 4 m). Average historical sounding point densities for each whole study site were 109 pts km^{-2} , 89 pts km^{-2} , 422 pts km^{-2} , 268 pts km^{-2} , 326 pts km^{-2} for the UFK, LFK, STT, BI, and Maui, respectively. Therefore, we used the locations of the historical soundings to extract modern elevation values from the LiDAR digital elevation models. This approach is more accurate than creating an interpolated model surface (or DEM) from the historical data and then determining elevation

change from two interpolated surfaces. Digital data files containing the XYZ coordinates for historical elevations were used with Spatial Analyst Tools in ArcMap 10.2.2 to extract LiDAR elevation values at the XY locations of historical soundings to create a single data file that contained the X and Y coordinates and the corresponding historical and LiDAR elevation values (see Supplemental Methods Section 1.2 for processing steps).

2.6 Calculation of elevation change

The data files created during the extraction process in Section 2.5 were used to calculate elevation changes (Z_{change}) by subtracting the historical elevation data from the corresponding modern elevation data via Eq. (1).

$$Z_{\text{change}} = \text{modern LiDAR elevation data point} - \text{historical elevation data point} \quad (1)$$

Using this equation, negative values indicate loss of seafloor elevation and positive values indicate gain of seafloor elevation. The resulting data files for each study site are located in Tables S1, S2, S3, S4, and S5. These files contain data columns for the historical H-sheet source, year of historical data value, latitude and longitude in geographic and UTM coordinates, historical elevation values (m), modern LiDAR elevation values (m), and the difference in meters (Z_{change}) between historical and modern elevations, as well as vertical and horizontal datum information (see Supplemental Methods Section 1.3 for processing steps). These data sets were used for elevation change analysis of each study site including calculation of mean elevation change and analysis of elevation change by habitat type. We note that much reef degradation contributing to elevation change likely occurred after 1970 (Gardner et al., 2003; Bruno and Selig, 2007; Jackson et al., 2014). Therefore, data sets containing pre-1970's data (Table 3) could be biased toward lower annual elevation and volume-change rates.

2.7 Calculation of elevation change statistics for study sites and habitat types

We used the XYZ_{change} (northing, easting and Z_{change}) data sets created in Section 2.5 for elevation analysis of each study site and of each habitat type within each study site. Mean elevation change and standard deviation were calculated for the total area of each study site using all Z_{change} data points. We used benthic habitat maps for the Upper and Lower Florida Keys from the Florida Fish and Wildlife Conservation Commission (2015), and for the USVI and Maui from NOAA (Kendall, 2001a, b; Battista and Christensen, 2007), to delineate the boundaries of all habitat classes within each site. We calculated elevation-change statistics from the data points included within or on the boundary of each habitat, including maximum elevation losses and gains, total number of elevation-loss data points, mean elevation loss and standard deviation, total number of elevation-gain data points, mean elevation gain and standard deviation. We also calculated elevation-change statistics for combined habitat classes within each study site that included only coral dominated substrate (e.g., scattered coral rock in unconsolidated sediment, aggregate reef, reef rubble, individual or aggregate patch reefs, spur and groove, etc.).

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as well as for combined habitat classes that included only adjacent habitats (e.g., non-coral dominated substrate types such as sand, seagrass, macroalgae, pavement unconsolidated sediment, etc.). Coral-dominated substrate types within each study site that were combined for these calculations were denoted with an asterisk and adjacent habitats were indicated by the absence of an asterisk in data tables. We created an ArcMap 'model' to automate the XYZ_{change} data-point processing for calculation of elevation-change statistics to ensure consistency for each habitat class (see Supplemental Methods Section 1.4 for data processing steps).

2.8 Elevation-change surface model

We created a single elevation-change surface model for each study site to estimate seafloor volume change, using the XYZ_{change} data points calculated in Section 2.5. We used the Delaunay triangulation algorithm (in ArcGIS 10.2.2) to create a triangulated irregular network (TIN) from these data points. The TIN consists of a comprehensive, three-dimensional network of triangles spanning the entire data set. The three dimensional location of the vertices of each triangle was determined by using the XY data to establish its horizontal position and the Z_{change} data to establish its vertical position in the network of triangles. TIN modelling allows for placement of nodes over irregular surfaces allowing for higher resolution over surface areas that are highly variable (such as coral reefs). Delaunay triangulation creates the triangle network such that no vertex lies within the interior of any of the circumcircles of the triangles in the network to avoid creation of long, thin triangles that can degrade surface resolution (<http://pro.arcgis.com/en/pro-app/help/data/tin/tin-in-arcgis-pro.htm>). Figure 3 shows examples of (a) the XYZ_{change} data plot, (b) the three dimensional TIN model developed from the XYZ_{change} data, (c) a sub-section of the TIN model, and (d) a horizontal cross-section view of the TIN model sub-section for the Upper Florida Keys study site. In Figs. 3b, c and d, the zero elevation-change plane lies between positive elevation-change values (denoted in blue tones) and negative elevation-change values (denoted in red tones). The gray areas in Fig. 3b and c and the dashed lines in Fig. 3d indicate all elevation-change values between +0.5 m and -0.5 m (90% RMSE). See Supplemental Methods Section 1.5 for data processing steps.

2.9 Calculation of volume change for study sites

We calculated volume changes (in units of millions of cubic meters, Mm³) for each study site using the surface models created in Section 2.8. Maximum volume-change calculations included all elevation-change data. Minimum volume-change calculations excluded all elevation-change data within or equal to plus or minus 0.5 m (see Fig. 3 for Upper Florida Keys example). The 0.5 m threshold was derived from our vertical error analysis (see Section 2.11). We calculated volume-change for 4 cases based on placement of a reference plane within the surface model as follows:

- 1) gross accretion (maximum volume): plane height set to 0.0 m, volume calculated above the plane.
- 2) gross erosion (maximum volume): plane height set to 0.0 m, volume calculated below the plane.

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- 3) gross accretion (minimum volume): plane height set to +0.5 m, volume calculated above the plane.
- 4) gross erosion (minimum volume): plane height set to -0.5 m, volume calculated below the plane.

For example, case 1 for the Upper Florida Keys included all of the elevation-change data above a 0 m plane that bisects the dashed lines in Fig. 3d, while case 2 included all of the data below that 0 m plane. Case 3 included all of the blue-toned data above the upper dashed line denoting the +0.5 m plane in Fig. 3d, while case 4 included all of the red-toned data below the lower dashed line denoting the -0.5 m plane. Maximum net volume changes (Mm^3) were calculated by summing the results of cases 1 and 2 for each study site. Minimum net volume changes (Mm^3) were calculated by summing the results of cases 3 and 4 for each study site. Area-normalized volume changes (Mm^3/km^2) were calculated by dividing net volume changes for each study site by its total area. See Supplemental Methods Section 1.6 for data processing steps. Seafloor accretion and erosion is a function of total mass balance in coral reef ecosystems (Schlager, 1981). However, we did not convert volume to mass of calcium carbonate because volume-change includes sediment compaction, loss due to mortality and degradation of framework-building coral colonies, and sediments of various porosities. Therefore, our volume changes are limited to approximations of mass changes.

2.10 Calculation of volume change for habitat types

We used the benthic habitat maps referenced in Section 2.7 (also used for elevation change calculations) to delineate habitat boundaries for calculation of volume changes for each habitat class within each study site. Habitat classes within each map were represented by individual polygons. We created new TIN models for each habitat polygon that only covered the areal extent of the specific habitat class polygon where it intersected the whole study site TIN. We calculated minimum and maximum volume changes for gross erosion and gross accretion in each habitat class using the 4 reference plane cases described in Section 2.9. We calculated volume changes for combined habitat classes within each study site including combined coral-dominated substrate and combined adjacent habitat using the same habitat combinations and procedures similar to those used for combined habitat elevation-change statistics described in Section 2.7 and using processing steps in Supplemental Section 1.7.

2.11 Vertical error analysis

U.S. Federal Standards were applied for all vertical and horizontal data transformations and error analyses. Our vertical error analysis included error terms for:

- 1) $RMSE_{\text{sounding}}$ = uncertainty for each historical data set as determined from our analysis of repeat measurements that were performed by the original surveyors at the time of data collection.

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- 2) $RMSE_{LiDAR}$ = uncertainty for modern LiDAR data sets that was determined by independent validation of airborne LiDAR measurements with in-water acoustic sounding measurements performed at the time that the LiDAR data was collected and reported in the metadata for these data sets, and
- 3) $RMSE_{VDatum}$ = uncertainty from transformation of data to a common vertical datum as calculated using VDatum version 3.6 (NOAA National Ocean Service, 2016) for each individual data set.

These uncertainty values (RMSE values) are specific to each data set and are reported in Table 5.

We determined $RMSE_{Sounding}$ for each historical data set from repeat sounding measurements collected by the original surveyors. When historical sounding data were collected, repeat surveys were performed along select transect lines and/or additional soundings were collected along intersecting transects for the purpose of determining vertical accuracy. Only maximum difference of repeat data points was reported as accuracy information in the historical data set descriptive reports. We, therefore, re-analysed all of the historical repeat and cross-track line survey data from the original historical data sets to perform a more rigorous, systematic vertical-error analysis (rather than simply using the reported maximum difference). We calculated the mean difference in depth between all pairs of repeat measurements within each historical data set, and used these data to calculate an $RMSE_{Sounding}$ for each data set using Eq. (2) whereby $d_{i,1}$ and $d_{i,2}$ were paired repeat depth measurements and n = the number of sounding-point pairs used for each location (see Supplemental Methods Section 1.8 for procedures to identify repeat sounding measurements).

$$RMSE_{Sounding} = \sqrt{\frac{\sum_{i=1}^n (d_{i,1} - d_{i,2})^2}{n}} \quad (2)$$

The number of sounding-point pairs used for each location was 40, 253, 40, and 51 for the UFK, STT, STC and Maui, respectively. The LFK was excluded from this analysis because no adjacent points were separated by 5 m or less. Implicit in this approach is the assumption that the points in each pairing represent two independent depth measurements at approximately the same location. Therefore, the mean difference in depth between all pairs should not be significantly different from 0 m. For each study site, we performed a 2-tailed t -test at the $\alpha = 0.05$ level on the set of depth differences between paired points to test the null hypothesis of a zero mean difference.

t -tests were performed using Matlab v8.4.0 (R2014b). All of the $RMSE_{Sounding}$ values ranged from 13 to 32 cm, and are reported in Table 5 along with t -tests results.

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The maximum cumulative uncertainty (MCU) reported by NOAA National Ocean Service (2016) for operational VDatum regions of South Florida and the Virgin Islands are 9.6 cm and 11.8 cm, respectively. Our calculated $RMSE_{VDatum}$ for the UFK, LFK, STT and BI study sites fell within reported MCU values (Table 5). No vertical transformations were performed for the Maui data because both historical and modern elevation data were collected and reported relative to MLLW; therefore, $RMSE_{VDatum}$ was excluded from vertical error estimates for this study site.

We followed the general approach used by the U.S. Army Corps of Engineers (Byrnes et al., 2002) to calculate composite root-mean-square errors ($RMSE_{Total}$) for each study site (Table 5) according to Eq. (3) to provide conservative estimates of elevation changes based on combined sources of uncertainty.

$$RMSE_{Total} = \sqrt{RMSE_{Sounding}^2 + RMSE_{LIDAR}^2 + RMSE_{VDatum}^2} \quad (3)$$

Our average $RMSE_{Total}$ (Table 5) for all study sites was 0.29 m, and ranged from 0.20 m to 0.37 m. Our average $RMSE_{Total}$ (0.29 m) was similar to that reported for lidar and acoustic sounding data and half the reported value for previous studies that used nautical chart data to create a digital elevation model for examining the response of a reef to sea level rise (Leon et al., 2013; Hamylton et al., 2014). We then calculated a more conservative $RMSE_{Total}$ for each study site. We considered the $RMSE_{Total}$ values from each study as proxies for the standard deviations. Data within plus or minus one standard deviation of the mean encompasses approximately 68% of the variability in a normal distribution; and data within plus or minus 2 standard deviations of the mean encompasses approximately 95% of the variability. We used the Normal Inverse Cumulative Distribution Function to calculate that 90% of our elevation change values would occur within plus or minus 1.65 standard deviation of the mean. We then multiplied the $RMSE_{Total}$ values by 1.65 (denoted $1.65 \times RMSE_{Total}$) to capture approximately 90% of the variability in the depth differences. The average $1.65 \times RMSE_{Total}$ for all study sites was 0.48 m, which we rounded to 0.5 m and applied to all of our study sites for calculation of minimum volume changes.

2.12 Independent vertical error validation through pavement analysis

Within our study sites, the most stable areas were likely those classified as pavement or bedrock. We performed an analysis of these habitat types to independently estimate the potential vertical error associated with comparing historical and modern sounding data. We caution that this type of analysis does not constitute a true control because no subaqueous surface areas (including stable pavement or bedrock) are exempt from elevation change. For example, our data indicated areas where

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pavement had been exposed likely due to erosion of overlying sediments, as well as areas where pavement had been buried likely by deposition of sediments or growth of corals, etc. However, areas were identified in each data set where little to no elevation change were also observed. We examined habitats labelled 'pavement' in the UFK and LFK, 'uncolonized pavement' in STT, 'colonized pavement' in BI, and 'coral pavement' in Maui. We filtered the elevation-change data points for these habitats to include only elevation changes of less than +/- 0.5 m (1.65 x RMSE_{Total}). We then calculated the average difference and standard deviation between these points for each data set.

More than 50% of elevation-change points for pavement in the UFK, STT, and BI; 17% in the LFK; and 23% in Maui showed elevation changes within our 1.65 x RMSE_{Total} of 0.5 m. Standard deviations for these locations were all within our RMSE_{Total} of 0.29 m. Mean differences between historical and modern elevation data in these locations were very small (ranging from 3 to 6 cm, Table 6), indicating that vertical resolution and accuracy of historical and modern elevation data are comparable. Large standard deviations relative to the means and histograms showing skewed distribution of data points from this analysis (Fig. 4) demonstrate that all areas of pavement are not stable and, therefore, should not be considered a true control.

2.13 Horizontal error analysis

No horizontal error was reported for any historical data sets. Our historical sounding data sets ranged from the 1930's to 1980's. Therefore, we determined the potential horizontal error associated with our oldest data sets from the 1930's in the Florida Keys as an estimate of maximum horizontal error for all study sites. The Florida Keys historical soundings were measured using the least accurate horizontal positioning methods and had average point densities that were more than 50% lower than the other study sites.

The original horizontal datum for data sets from the Florida Keys was North American Datum 1927 (NAD27). Transformation of data from NAD27 to NAD83 using NOAA National Ocean Service program NADCON introduces no more than 15 cm of uncertainty in the continental United States (Dewhurst, 1990). The Annual Report of the U.S. Coast and Geodetic Survey 192 (1880) indicates that it was possible under normal controls to measure distances (using triangulation) with an accuracy of 1 meter, and the position of the plane table could be determined within 2 to 3 meters of its true position (Shalowitz, 1964). The horizontal resolution of LiDAR data is reported as better than 1m (Brock et al., 2006a and b; Brock et al., 2007; Fredericks et al., 2015a, b). A sum of these estimated sources of error is approximately 5 m. We chose to sum these estimated sources of error to provide a more conservative error estimate rather than to calculate a horizontal RMSE. This error estimate is similar to the maximum offset of 4.8 m between the historical and modern measurements of a bridge structure located south of Lower Matecumbe Key in the UFK as depicted on a 1934 H-sheet and on the 2016 World Imagery, identified during visual inspection of H-sheets described in Section 2.2.

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Horizontal error of approximately 10 m is typically reported for data plotted at a 1:20,000 scale (Anders and Byrnes, 1991; Fletcher et al., 2003; Morton et al., 2004). Therefore, we performed a horizontal shift analysis to test the potential impact for systematic plus random horizontal error of up to 10 m that represents an approximate doubling of our sum of estimated sources of error (5.0 m). Historical XYZ elevation data from the Upper and Lower Florida Keys were shifted by 10 meters to the north, south, east and west by adding 10 m to, and subtracting 10 m from, UTM northings and eastings for each data point (26,341 and 1,688 points for the Upper and Lower Florida Keys, respectively). This exercise generated 4 new, experimental historical XYZ elevation point-data sets that simulate up to 10 meters of horizontal error in each of 4 directions. The area of the un-shifted LiDAR DEMs for each site were clipped to each of the four shifted historical data sets generated for each study site, resulting in 4 new pairs of historical and modern elevation data sets for each study site. Elevations from the LiDAR DEMs were then extracted at each historical point location for each paired historical and modern data set, and used to calculate elevation differences between the shifted historical soundings and un-shifted LiDAR data sets as described in Section 2.6. We created new TIN models from the shifted XYZ_{change} point-data sets and calculated volume changes for each of these data sets using the TIN modelling process and surface volume analysis described in Sections 2.8 and 2.9.

Results from the horizontal shift analysis indicate that 10 m of horizontal error produces no more than 10% difference in net and area-normalized volume change calculations in the Upper Florida Keys, and up to a 21% difference in the Lower Florida Keys (Table 7) likely due to the lower density of data points over a smaller geographic area. The LFK had the lowest historical sounding point density of all data sets at 89 pts km⁻² and the smallest study site area of 19 km². Imparting 10 m of horizontal error in these experimental data sets does not change the general conclusion of our study indicating high magnitude of net erosion at these study sites. Our results are consistent with reports that over large areas (such as in our study), random errors largely cancel-out relative to change calculations derived from two surfaces (Byrnes et al., 2002).

3 Results and observations

3.1 Regional-scale loss of mean seafloor elevation and volume

Loss of seafloor elevation and volume, and transition from net accretion to net erosion, has occurred at all study sites (Table 8). Mean seafloor elevation losses for whole coral reef ecosystems in our study ranged from -0.09 m to -0.8 m. Note that mean elevation changes ('Mean elevation-change' columns in Tables 8 and 9) represent the net change encompassing all negative (elevation losses) and positive (elevation gains) values. Figures 5, 6 and 7 show the complex spatial distribution and large range of elevation gains and losses across the study sites. Individual measurements of elevation change were often very large (greater than 1 meter, see minimum and maximum elevation loss and gain data by habitat in Table 9). Maximum

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elevation losses exceeded 4.0 m and maximum elevation gains exceeded 6.5 m at all study sites. Therefore, standard deviations for mean elevation changes were high and ranged from 0.7 m to 1.5 m for all sites.

5 Net volume losses were also observed in all regions indicating export of sediments from these systems (Table 1). Minimum volume changes (calculated by excluding elevation change data within a vertical range of ± 0.5 m, see 1.65 x RMSE calculations in Table 5) provide conservative estimates of net volume losses ranging from 0.2 to 52.8 Mm^3 for all study sites. Maximum volume changes (including all elevation-change data) indicate net volume losses ranging from 3.4 to 80.5 Mm^3 for all study sites.

10 3.2 Changes in mean seafloor elevation and volume by habitat type

15 We analysed 118,710 elevation change data points from 60 habitats across all five study sites. Fifty-nine of these habitats showed net elevation change, 46 (77%) showed net elevation losses, and 13 (22%) showed net elevation gains (Table 9). The 'Mean loss' column in Table 9 (that includes only elevation loss values within habitats) indicates that only two habitats showed mean losses less than our $\text{RMSE}_{\text{Total}}$ of 0.29 m (STT reef rubble and BI seagrass). Only 14 habitats showed mean losses less than our 1.65 x $\text{RMSE}_{\text{Total}}$ of 0.5 m (that encompasses 90% of the variability). Therefore, mean losses in 97% of the habitats we analysed were greater than our vertical $\text{RMSE}_{\text{Total}}$ of 0.29 m, and 77% of the habitats we analysed showed mean losses greater than 1.65 x $\text{RMSE}_{\text{Total}}$ or 0.5 m. In several cases, and particularly associated with coral-dominated substrate, mean losses exceeded one meter. Conversely, if one examines only elevation gain values within habitats ('Mean gain' column in Table 9), 92% of the habitats show showed mean gains greater than our $\text{RMSE}_{\text{Total}}$ of 0.29 m and 60% showed mean gains greater than our 1.65 x $\text{RMSE}_{\text{Total}}$ of 0.5 m.

20 Greatest mean elevation losses were generally associated with shallow, coral-dominated habitats (Tables 8 and 9) at all study sites consistent with observations of general flattening of reef topography (Alvarez-Filip et al., 2009), and observations of decreasing abundance of reef-building corals (Gardner et al., 2003; Bruno and Selig, 2007; Jackson et al., 2014; Sparks et al., 25 2015). However, greatest net volume losses at most study sites were generally associated with adjacent (non-coral dominated) habitats despite smaller mean elevation losses. This apparent contradiction is due to the greater areal extent of these habitats (Tables 8 and 10). Maximum values of area-normalized volume change calculated using all elevation change data (Table 8) indicate that volume loss in adjacent habitats was 40% to 100% of losses observed in coral-dominated substrate. We calculated the percent of each study site classified as coral-dominated substrate to estimate the potential contribution of loss of framework-building coral species to total net volume loss (coral-dominated habitat classes were denoted in Tables 9 and 10 with an asterisk). For example, the Upper Florida Keys coral-dominated habitat classes included scattered coral rock in unconsolidated sediment, aggregate reef, reef rubble, individual or aggregate patch reefs, and spur and 30

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groove habitat. The other study sites included similar lists of coral-dominated habitats. We included reef rubble as a coral-dominated substrate in our calculations because, for example, in the Florida Keys many areas of reef rubble contain large skeletal fragments of *Acropora palmata* and other coral species, and we note that framework-building coral species such as *Acropora sp.* declined significantly throughout the Caribbean and Western Atlantic during the time periods of our study (Jackson et al., 2014). Areal extent of coral-dominated substrate was only 8% to 15% of the total study area in the JFK, LFK, and STT study sites, and contributed up to only 26% of the total net volume loss. Most of the volume loss in these areas was associated with sediment loss from non-coral dominated (adjacent) habitats such as areas of unconsolidated sediments, seagrass, and uncolonized pavement. Areal extent of coral-dominated substrate was higher at the Maui study site (57%) and contributed more than 50% to net volume loss, and adjacent habitats accounted for the remaining volume loss. The considerable loss of seafloor volume in adjacent habitats at these study sites as well as in coral-dominated habitats, and large total net volume losses suggests that physical erosion and export of sediments is a likely driver of much of the volume loss we observed.

The BI study site had the highest areal extent of coral-dominated substrate (91%) that contributed more than 90% to the total net volume loss, suggesting that degradation of framework-building corals may be the primary contributor to volume loss at this study site. Recent photographic surveys (C. Storlazzi, USGS, 2015) along the eastern coast of Buck Island show large stands of *Acropora palmata* coral colonies that have died and toppled over, but remain largely in tact and in place on the seafloor along the northeastern side of the island from approximately the eastern-most point to at least the mid-point of the island (Fig. 8a, b, and c), consistent with our observation of greater elevation loss in that area (Fig. 6c). The southeastern side of the island, from the eastern-most point to at least the barrier break, was characterized by much more live *A. palmata* coral (Fig. 8d, e, and f), also consistent with our observation of increased elevation in that area (Fig. 6c). These photos illustrate how loss of topographic complexity (as described by Alvarez-Fillip et al., 2009) can cause elevation and volume loss without material export. The live coral colonies clearly show relatively high elevation and colony volume that consists of both coral branches as well as very large open (pore) spaces between the branches. As large colonies topple, the coral branches break and the colony compacts causing a loss in elevation and volume as the open spaces between the branches are minimized. Large coral fragments are much harder to transport than sediments, typically require high-energy storm events for movement, and are, thus, not as easily exported from the system. Additionally, coral rubble-fields generated from toppling corals can create a rubble pavement on top of sand making it more difficult to transport. Mean elevation and volume losses were much lower at the BI study site than at the other study sites indicating that much less sediment was exported from the system, consistent with our observations of large areas of physically-toppled coral colonies that remain mostly in place on the seafloor. This type of physical coral degradation is very different from degradation of reef structure due to bioerosion by reef grazers such as parrotfish and *Diadema sp.* sea urchins that directly reduce coral and reef structure to sand-sized sediments that can then be more easily transported and exported by physical processes, and from chemical bioerosion caused by some species of sponges and endolithic algae that dissolve carbonate material (Decarlo et al., 2015; Enochs et al., 2015;

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Reyes-Nivia et al., 2013; Wisshak et al., 2013; Wisshak et al., 2012; Tribollet et al., 2009). As population-abundances of bioeroders increase and decrease in a given location, so do rates of bioerosion caused by these organisms (Mumby, 2009). Populations of grazing bioeroders have decreased at the BI study site and throughout most of the Caribbean during the time periods of our study (Table 1) that may account for the lower export rates at this study site because coral and coral rubble may be reduced to sand at a slower rate. Visual inspection of study sites in the Florida Keys shows similar evidence for physical toppling of corals in rubble fields. However, parrotfish populations recently increased in the Florida Keys (Table 1) and rates of chemical bioerosion have increased since pre-industrial times (Enochs et al., 2015) which may help expedite breakdown and physical transport of reef materials out of the system, consistent with the higher volume losses observed in the Florida Keys.

Along the Florida Keys reef tract within Biscayne National Park, Florida and the Florida Keys National Marine Sanctuary, mean elevation and volume losses occurred in 9 of 11 habitat classes in the Upper Florida Keys (UFK) reef tract (Fig. 5a, b) and in 6 of 9 classes in the Lower Florida Keys (LFK) reef tract (Fig. 5c, d) including coral habitats, and adjacent habitats such as unconsolidated sediments, pavement previously covered by sediments or coral, and seagrass. Largest mean elevation losses occurred at shallow patch and aggregate reefs, coral-dominated and reef rubble habitats, consistent with documented declines in abundance of large framework-building corals over the past several decades (Jackson et al., 2014). Largest net volume losses occurred in seagrass and unconsolidated sediment habitats. Mean elevation and volume gains occurred in deep water habitats of the UFK and LFK sites including offshore aggregate reefs in the LFK near a sanctuary preserve area, at the base of spur-and-groove habitat along fore-reef slopes, and where relic spur-and-groove formations in-filled with sediments indicating transport of reef sediments down the fore-reef slope and export offshore (Fig. 9). Mean total elevation loss was lowest at the UFK study site. However, mean elevation losses decreased from upper (-0.4 m) to central (-0.3 m) sub-regions of the UFK, and mean elevation increased slightly in the lower sub-region (0.1 m) primarily associated with seagrass habitat (Fig. 5a, b). Notably, the lower sub-region is further away from high-density population areas north of the study site and near an area of the middle Florida Keys identified as a possible refuge from ocean acidification due to seagrass productivity (Manzello et al., 2012). The LFK site included the Looe Key National Marine Sanctuary and Special Protection Area (Fig. 5c). Net elevation and volume losses were similar to the central sub-region of the UFK possibly due to close proximity to high-density population areas in the Lower Florida Keys. However, the LFK was the only study site that showed net accretion in combined coral habitat classes. Accretion is partially attributed to deep reef and spur-and-groove habitat that has been buried by sand (Lidz et al., 2007). Redistribution of reef materials and erosion of the Florida reef tract is corroborated by field observations of movement and deposition of meters-thick sand deposits likely due to hurricanes and by exposure of older reef material from erosion and transport (Shinn et al., 2003). However, accretion was also observed on offshore aggregate reef habitat near the Special Protection Area.

Mean elevation and volume loss occurred in 16 of 17 habitat classes in STT (Fig. 6a, b). In STT, small, localized areas of

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coral-dominated substrate showed gains in elevation. However, greatest mean elevation losses occurred in coral-dominated habitats and near the central coastline where harbour and shipping channels exist. Mean elevation and volume gains only occurred on un-colonized bedrock possibly due to transport and deposition of sediments. However, uninhabited Buck Island National Reef Monument and Marine Park, St. Croix USVI (BI) showed less mean elevation and volume loss than all other sites with losses limited to 4 of 11 habitat classes including 3 coral habitats (Fig. 6c, d). The study period for BI is approximately 10 years shorter than for nearby STT. Greatest mean elevation gains in BI occurred along linear reef near the shoreline. Most elevation and volume gains occurred within Buck Island National Reef Monument and Marine Park boundaries (Fig. 6c) suggesting that distance from populated areas combined with managed protection has limited losses at this site.

Mean elevation and volume loss occurred in 10 of 12 classes in Maui (Fig. 7a, b). Mean elevation and area-normalized volume losses were at least 2 to 3 times greater, respectively, than all other study sites and occurred over a shorter time-frame. These greater losses may be caused by higher sediment export rates due to a combination of higher wave energy, physical erosion and a narrow shallow shelf surrounding the island allowing sediment to be more easily transported offshore into deep water, as has been observed in other high energy reef environments (Morgan and Kench, 2014; Perry et al., 2015). Greatest mean elevation losses were associated with coral-dominated habitat as well as 'not classified' habitat located in the bank/shelf zone that may be impacted by slumping of materials along steeply sloping areas. Elevation and volume gains occurred in mud and rubble habitats, and may be associated with terrigenous sediment transport from the island.

Examination of histograms for pavement analysis data support the general observations for each of our study sites. Histograms for the UFK, LFK, STT and Maui (Fig. 4a, b, c, e) are all skewed toward negative values, consistent with regional-scale trends of seafloor elevation loss and export of sediments at these sites. While BI (Fig. 4d) showed a more even distribution of points among elevation losses and gains consistent with the lower regional-scale mean elevation losses observed at this study site, and suggestive of redistribution and less export of sediments within the system. Notably, of the five study sites we examined, the 'colonized pavement' in BI was the only pavement habitat to show a very small increase in elevation that could be due either to coral growth on the pavement or accumulation of sediments.

4 Discussion

Our results include elevation and volume changes caused by chronic erosion and accretion processes that occur slowly over time frames of months to decades such as changes in carbonate production rates, bioerosion, chemical erosion from carbonate dissolution, degradation of large framework building coral colonies, and physical movement of reef sediments due to persistent oceanographic conditions such as waves and currents. Our results also include changes caused by episodic events that occur over very short time frames of minutes to days and often cause large changes in elevation, that alter habitat

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distribution and affect process modelling for coastal hazards. Examples include dredging and infilling of channels and coastal harbours, deposition of terrigenous materials from landslides and run-off, slumping and relocation of seafloor materials at steeply sloping locations, storm erosion and deposits. These multiple processes cause direct changes in seafloor accretion and erosion; and multiple factors drive changes in the rates of these processes (including, for example, impacts

5 from coastal development, overfishing, nutrient enrichment, coral bleaching and disease, climate change, ocean acidification, cultural and economic resource values, etc). Physical changes in seafloor structure across reef ecosystems and its causes are highly variable due to the large spatial and temporal variability of these processes, the complex interactions among processes within and among adjacent habitats, and uneven responses within and between species and habitats to multiple local, regional and global impacts. Accurately measuring these physical changes are difficult due to the diversity and complexity of

10 the resulting habitat structure within a coral reef ecosystem. The complex spatial distribution and large range of elevation gains and losses we observed across our study sites, as well as our assessments of error, indicate that our methods provide an effective means for measuring the changing dynamics of accretion and erosion at whole ecosystem scales with high enough spatial resolution to capture changes that reflect the diverse responses of accretion and erosion processes to multiple driving factors. Our results can, therefore, be used to measure changes in whole system accretion and erosion required to determine

15 regional-scale impacts from sea level rise. Additionally, our methods can be used for characterizing changes in the complex seafloor structure of coral reef ecosystems required for development of hydrodynamic and other numerical models for assessing and predicting the impact of reef degradation on the vulnerability of coastal communities to hazards caused by storms, waves, sea level rise and erosion.

20 More difficult is the attribution of change to cause because physical change in seafloor structure represents the integrated, and sometimes delayed, result of many combined processes of and impacts to carbonate production, accretion and erosion. Carbonate production and erosion rates developed from small-scale and/or short-term process studies provide local snapshots in time that may not capture the variability of these rates in the whole system and, therefore, may skew carbonate budget results when extrapolated to larger areas or longer time periods. Integrative process-studies conducted over large

25 areas can indicate the net response of a system, but often do not accurately capture the contribution from individual processes in a system required to attribute change to cause. Furthermore, our knowledge of multi-stressor impacts to carbonate production and erosion is emerging, but largely limited to experimental results from laboratory or mesocosm experiments that are difficult to extrapolate to whole ecosystem scales. Many geological studies of reef systems measure long-term changes in carbonate accretion, erosion and carbonate budgets. However, there is a disconnect between the temporal resolution of geologic studies (decades to millions of years) and the temporal resolution of most process studies

30 (from minutes to decades) that makes it difficult to attribute change in the geologic record to contemporary processes over time periods that are informative for management decisions.

We emphasize that a key limitation of our elevation-change analyses is that they do not attribute change to cause. Detailed

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analysis of the processes causing elevation-change in these systems is beyond the scope of this paper and should be undertaken in future studies. However, we provide general comparisons of our elevation and volume-loss measurements to individual process rates from the literature to provide context for the magnitude of our results. These comparisons also demonstrate the potential value of knowing net whole system change when accounting for and identifying individual processes, for identifying missing gaps in erosion/accretion budgets, and serve as an example of how our results may be used in future studies to improve erosion and accretion budgets in coral reef ecosystems.

Over 90% of the habitats we analysed in our study showed statistically significant elevation changes with a net result of elevation loss. Accretion of a reef ecosystem over time occurs when the balance of accumulation of reef materials and sediments (that increases material elevation and volume) exceeds erosion and loss of the eroded material from the system (that decreases materials elevation and volume). Our observations of mean seafloor elevation and volume loss indicate that more materials are being eroded and exported from these coral reef systems than are accumulating. Erosion of both coral-dominated substrate and non-coral substrate suggests that the current rate of carbonate production is no longer sufficient to support net accretion of coral reefs or adjacent habitats. Calculation of annual mean seafloor elevation losses for each study site from our total mean elevation change values in Table 8 (column 3) and the historical-to-modern time periods of data sets for each site, Eqs. (3 - 7), shows that mean seafloor elevation decreased by -1.5 to -6.3 mm yr⁻¹ over 33 to 68 years at Atlantic and Caribbean sites, and by -21.1 mm yr⁻¹ over 38 years at the Pacific site (Fig. 10).

$$\text{UFK} = -0.1 \text{ m} / 68 \text{ years} = -1.5 \text{ mm yr}^{-1} \quad (-5.9 \text{ mm yr}^{-1} \text{ upper sub-region, } -4.4 \text{ mm yr}^{-1} \text{ central sub-region}) \quad (3)$$

$$\text{LFK} = -0.3 \text{ m} / 66 \text{ years} = -4.5 \text{ mm yr}^{-1} \quad (4)$$

$$\text{STT} = -0.3 \text{ m} / 48 \text{ years} = -6.3 \text{ mm yr}^{-1} \quad (5)$$

$$\text{BI} = -0.09 \text{ m} / 33 \text{ years} = -2.7 \text{ mm yr}^{-1} \quad (6)$$

$$\text{Maui} = -0.8 \text{ m} / 38 \text{ years} = -21.0 \text{ mm yr}^{-1} \quad (7)$$

To estimate how many years of reef accretion may have been lost due to erosion, we divided our total mean elevation-losses (mm) from Table 7 (column 3) by published average Holocene reef accretion rates of 2.6 and 10 mm yr⁻¹ for Caribbean/Atlantic and Pacific reefs, respectively, in Eqs. (8 - 12) (Shinn et al., 1977; Buddemeier and Smith, 1988).

$$\text{UFK} = -0.1 \text{ m or } 100 \text{ mm} / 2.6 \text{ mm yr}^{-1} = 38 \text{ yrs} \quad (8)$$

$$\text{LFK} = -0.3 \text{ m or } 300 \text{ mm} / 2.6 \text{ mm yr}^{-1} = 115 \text{ yrs} \quad (9)$$

$$\text{STT} = -0.3 \text{ m or } 300 \text{ mm} / 2.6 \text{ mm yr}^{-1} = 115 \text{ yrs} \quad (10)$$

$$\text{BI} = -0.09 \text{ m or } 90 \text{ mm} / 2.6 \text{ mm yr}^{-1} = 35 \text{ yrs} \quad (11)$$

$$\text{Maui} = -0.8 \text{ m or } 800 \text{ mm} / 10 \text{ mm yr}^{-1} = 80 \text{ yrs} \quad (12)$$

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These calculations indicate that total mean elevation losses that occurred over 33 to 68 years at our study sites represent the loss of approximately 35 to 115 years of reef accretion. These coral reef ecosystems have lost pace with historical global mean sea level rise of 1.7 mm yr⁻¹ between 1901 and 2010, and will be unable to keep up or catch up with current or projected rates of 3.2 mm yr⁻¹ (1993-2012) and 4.5 mm yr⁻¹ (mid-century, RCP4.5), respectively (Church et al., 2013).

Perry et al. (2013) estimated modern reef accretion and erosion rates on 19 Caribbean reefs based on carbonate production and bioerosion, and reported a maximum erosion rate of -1.17 mm yr⁻¹. This maximum erosion rate could account for only 20% and 27% of erosion observed in the upper and lower sub-regions of the UFK, respectively; for only 26% of erosion observed in the LFK, 43% at BI, and 19% at STT. Such a comparison illustrates that this maximum bioerosion rate (1) cannot fully account for erosion loss at these study sites; (2) estimates the amount of erosion that is unaccounted for in these examples; and (3) identifies missing process gaps in that analysis. Similarly, recent regional-scale measurements of carbonate production and dissolution in the Florida Reef Tract show that dissolution alone could account for chemical erosion of up to approximately -0.7 mm yr⁻¹ in the northernmost reef tract (Muehlllehner, 2016), or approximately 12% and 16% of the erosion we observed in the upper and central sub-regions of the UFK study site, respectively. Applying combined maximum estimates for erosion considering bioerosion (Perry et al., 2013) and chemical dissolution (Muehlllehner, 2016), could account for only 32% to 43% of erosion in these sub-regions of the UFK. Enochs et al. (2015) developed a carbonate budget model of 37 reefs along the Florida Reef Tract that accounted for bioerosion by boring sponges, endolithic algae, and parrotfish as well as calcification by coral and crustose coralline algae. Eighty-nine percent of the reefs in their study showed net erosion, consistent with our observation of net erosion at the Florida Keys study sites. Their erosion rates for the Upper Keys, and Lower Keys were -1.474 kg m⁻² yr⁻¹ (or 0.00092 m³ m⁻² yr⁻¹) and -1.556 kg m⁻² yr⁻¹ (or 0.00097 m³ m⁻² yr⁻¹), respectively (assuming a bulk density of 1600 kg CaCO₃ m⁻³ from Hubbard (1992) for volume calculations). Our area-normalized, annual volume change (calculated from maximum net volume change in Table 8) for the UFK and LFK was 0.002 m³ m⁻² yr⁻¹ and 0.004 m³ m⁻² yr⁻¹, respectively. Enochs et al. (2015) erosion rates could account for 24% to 46% of the erosion we observed at the Florida Keys study sites. Harney and Fletcher (2003) determined sediment production from reef bioerosion rates for Kailua Bay, Oahu, Hawaii of 0.33 kg m⁻² yr⁻¹ (or 0.0002 m³ m⁻² yr⁻¹, assuming a bulk density from Harney and Fletcher (2003) of 1480 kg CaCO₃ m⁻³). Export of all bioeroded sediment based on their sediment production rate could account for less than 1% of our area normalized, annual volume change for Maui of 0.03 m³ m⁻² yr⁻¹. In these examples, results indicate that much of the erosion we observed at our study sites could be attributed to causes other than export of bioeroded sediments such as physical erosion and export of sediments that has been largely unaccounted for in these systems.

Previous studies indicate that, in some cases, higher sea level will facilitate production and transport of unconsolidated sediments shoreward, and growth of reef islands (Hopley and Kinsey, 1988; Hopley, 1992; Kench et al., 2014). Recent studies on 146 reef islands on 12 atolls in the central and western Pacific show that 106 of these islands have remained

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5 stable, while 40 have increased in size, and only 12 have decreased in size over the past few decades when sea level increased three to four times more than the global average (McLean and Kench, 2015). Kench et al. (2015) performed a detailed analysis of shoreline change on 29 islands of the Funafuti Atoll in the central, tropical Pacific. Their results showed no evidence of erosion with increasing sea level during the past 50 years, and that many of those islands have increased in size. Kench et al., (2015) also noted that stable and growing islands have a more erosion resistant island core (e.g. gravel islands) and periodic pulses of new sediment input, while those islands that have decreased in area have lost original island core material that is often less resilient (e.g., sand islands), and have no new sediment input. Our Maui study site showed the greatest volume loss over the shortest period of time (Table 8). Although Maui is a volcanic island, the coastal plains are composed primarily of late middle to late Holocene carbonate sands (Fletcher, et al., 2003). Studies of beach erosion along the Maui coastline show that beach width narrowed by 19% island-wide from 1949/50 to 1997/2002 due to erosion and alongshore transport of sand; and radiocarbon dating showed that no modern sand is transported onshore from the reefs (Fletcher et al., 2003). To our knowledge, no comprehensive studies that quantify seafloor sediment export have been undertaken in Maui. However, studies on shallow, fringing reefs along the west coast of Maui and south coast of Molokai, Hawaii indicate that strong currents produced by trade winds cause daily sediment resuspension and transport primarily alongshore, and offshore-directed currents and ebbing tides cause offshore transport of suspended sediments (Ogston et al., 2004; Storlazzi et al., 2004; Presto et al., 2006; Storlazzi et al., 2008). Large, high-energy winter and storm waves cause strong offshore transport of suspended material, and terrigenous sediment from the shore is also primarily transported offshore across the reef flat and fore reef (Storlazzi et al., 2008). Our results indicate net export of sediments from the coastal seafloor of Maui and support these previous observations that reef and terrigenous sediment is transported offshore and no new sediment from the reef is contributed to coastal beaches.

25 Sediment transport measurements in other coral reef ecosystems show large amounts of sediment export primarily due to physical oceanographic processes during both fair-weather (persistent) and storm conditions (Hubbard et al., 1981; Hubbard, 1986; Hubbard et al., 1990; Hubbard, 1992; Kench and McLean, 2004; Morgan and Kench, 2014), and suggest that physical erosion and export of sediments could account for much of the volume loss we observed at our study sites. We estimated sediment volumes for studies that reported mass (kg or metric tons) of sediment export based on a bulk density for reef sediment of 1600 kg m^{-3} (Hubbard, 1992) for comparative purposes; however, bulk densities are likely variable from location to location (e.g., Harney and Fletcher, 2003). For example, several studies on reefs around the island of St. Croix, U.S. Virgin Islands show that wave-induced oscillatory and unidirectional currents are the dominant process causing physical transport of sediments offshore, particularly during storms (Hubbard et al., 1981); and that annual storms can increase sediment transport by an order of magnitude higher than occurs during fair weather conditions (Hubbard, 1986). Short-term sediment transport measurements from 15 locations around St. Croix (including two sites near Buck Island) showed transport rates ranging from $14 \text{ to } 437 \text{ kg m}^2 \text{ yr}^{-1}$ ($\sim 0.009 \text{ to } 0.3 \text{ m}^3 \text{ m}^{-2} \text{ yr}^{-1}$) during non-storm conditions, and $146 \text{ to } 2431 \text{ kg m}^2 \text{ yr}^{-1}$ ($\sim 0.09 \text{ to } 1.5 \text{ m}^3 \text{ m}^{-2} \text{ yr}^{-1}$) during storm conditions (Hubbard et al., 1981). Results from studies that

5 incorporated carbonate production, bioerosion, reef accretion and sediment transport measurements in an open reef system in Cane Bay along the north shore of St. Croix showed average sediment export rates of $153 \text{ kg m}^{-2} \text{ yr}^{-1}$ ($\sim 0.1 \text{ m}^3 \text{ m}^{-2} \text{ yr}^{-1}$) considering both fair weather and storm export rates (Hubbard et al., 1990). Fair weather export rates from Cane Bay and nearby Salt River Bay (St. Croix, USVI) are 33 kg day^{-1} ($\sim 0.02 \text{ m}^3 \text{ day}^{-1}$) and 64 kg day^{-1} ($\sim 0.04 \text{ m}^3 \text{ day}^{-1}$), respectively; but
10 increased to 440 kg day^{-1} ($\sim 0.3 \text{ m}^3 \text{ day}^{-1}$) and 1115 kg day^{-1} ($\sim 0.7 \text{ m}^3 \text{ day}^{-1}$), respectively, during normal heavy weather that occurs several times a year (Hubbard 1992). However, passage of Hurricane Hugo in 1992, caused export of 336 metric tons ($\sim 210 \text{ m}^3$) and 2000 metric tons ($\sim 1250 \text{ m}^3$) of sediment from Salt River Canyon and Cane Bay, respectively, in only 4 to 6 hours (Hubbard 1992). Based on our maximum net volume change values (Table 8), our results indicate annual volume loss ranged from up to $103,030 \text{ m}^3 \text{ yr}^{-1}$ (at BI) to $2,118,421 \text{ m}^3 \text{ yr}^{-1}$ (Maui). Area-normalized, annual volume loss ranged from
15 $0.002 \text{ m}^3 \text{ m}^{-2} \text{ yr}^{-1}$ to $0.03 \text{ m}^3 \text{ m}^{-2} \text{ yr}^{-1}$, and was lower than the observed ranges in the St. Croix studies (Hubbard et al., 1981; Hubbard et al., 1990). Our lower values may result because our measurements reflect integration of variable short- and long-term processes over much longer time periods (decades) and much larger geographic areas that include transport and redistribution of sediments within these systems as well erosion and export. Our area-normalized, annual volume losses were much higher those measured during sediment flux studies on a 3.23 km^2 Maldivian reef platform system that showed an annual sediment export rate of $127,120 \text{ kg yr}^{-1}$ ($\sim 2 \times 10^5 \text{ m}^3 \text{ yr}^{-1}$, Morgan and Kench, 2014), and in eleven hoas of reef systems in the Keeling Islands (Indian Ocean) that showed annual sediment flux rates ranging from 44 metric tons per year ($\sim 28 \text{ m}^3 \text{ yr}^{-1}$) to 223 metric tons per year ($\sim 139 \text{ m}^3 \text{ yr}^{-1}$) (Kench and McLean, 2004). However, these studies were performed over very small areas and very short time periods (108 days to 13 months). Our long-term sediment export rates fall within the range of the few studies that quantified short-term sediment flux and export rates in other reef systems.

20 Studies of ancient reefs indicate that many were able to keep up or catch up with sea level rise (Neumann and Macintyre, 1985). However, ancient reefs that were exposed to local, regional and global environmental stresses were unable to keep up and drowned (Schlager, 1981; Hubbard, 1997; Kiessling and Simpson, 2011). Recent projections of reef response to sea level rise in the northern Great Barrier Reef using carbonate production rates primarily from the 1970's indicate that
25 shallower reef flats could become colonized by corals with a rise in sea level of 0.5 m, but begin to drown after 30 years with a rise of 1.2 m (Hamylton et al., 2014). However, these projections do not consider reduced rates of calcification due to local and global stressors and loss of carbonates from erosion processes. A recent study by Perry et al. (2015) showed that while remote coral reefs (such as the Chagos Archipelago reef systems in the Indian Ocean) that are largely isolated from human influence experience severe coral mortality from climate driven impacts like coral bleaching, most of these reefs recover very rapidly and continue to produce enough carbonate to keep up with present and future sea level rise. While our Maui study site is remote (geographically isolated), it is not isolated from human influence; and our results showed large erosion rates at this site suggesting that these reefs systems have not recovered well from impacts/degradation despite geographic
30 isolation. We observed lower erosion rates in reef ecosystems (and net accretion in some localized areas in the UFK and BI) that were managed, distant from human population centers, or associated with natural refuge zones. However, these lower

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rates did not prevent net regional-scale losses of seafloor elevation and volume, at our study sites. Vertical accretion rates vary from site to site within a given region, some localized areas may continue accreting, and other coral reef ecosystems may be able to maintain pace with sea level rise (Hopley and Kinsey., 1988; Hopley, 1992; Kench et al., 2014; McLean and Kench, 2015; Kench et al., 2015). However, modern carbonate production rates are an order of magnitude lower than Holocene averages (Perry et al., 2013), and are estimated to decrease by as much as 60% by mid-century (Langdon and Atkinson, 2005). Bioerosion and chemical dissolution of carbonates are projected to increase with ocean acidification (Hoegh-Guldberg et al., 2007; Eyre et al., 2014; Enochs, et al., 2015). Therefore, reef erosion rates are likely to accelerate over the coming decades.

The magnitude of regional-scale erosion we observed in these reef systems (Table 8) following world-wide declines and transitions in reef species composition, combined with projections for continued global reef degradation suggests the onset in the geologic record of an Anthropocene reef crisis as marked by significant reef volume loss in ancient reef systems (Kiessling and Simpson, 2011). As an example, we calculated the amount of the total Holocene reef deposit at the LFK site that has been lost since 1938 using geophysical data sets from Lidz (2000) and Lidz et al. (2007). The geologic history and evolution of the Florida Keys reef tract has been well characterized (e.g., Lidz 2008). The Florida Keys Holocene reef deposit lies on top of Pleistocene carbonate bedrock. The formation of late Pleistocene bedrock began more than 125,000 years ago when South Florida was submerged during a sea level high stand. During this time period carbonate bedrock production resulted from the formation and accretion of coral reefs and carbonate sediments. The development of Pleistocene bedrock was marked by alternating periods of submersion and sub-aerial exposure as sea level fluctuated from approximately 125,000 to 10,000 years ago; and the Holocene reef of South Florida began to form as the Florida shelf flooded when the most recent rise in sea level began approximately 10,000 years ago (Lidz et al. 2008). The Holocene reef of the Lower Florida Keys began forming approximately 6000 to 7000 years ago and lies on top of Pleistocene bedrock that was exposed in this area prior to 7000 years ago (Lidz et al. 1985). Seismic profiles were collected throughout the Florida Keys from 1997 through the early 2000's to measure the depth below the seafloor of the Pleistocene bedrock surface (Lidz et al. 2007); and a depth-to-Pleistocene-bedrock (DPB) surface was constructed from these seismic data and cores along the Florida Keys reef tract (available from the U.S. Geological Survey at <http://pubs.usgs.gov/pp/2007/1751/data/PP1751.zip>). The difference between the elevation of the seafloor surface and the elevation of the Pleistocene bedrock surface below the seafloor estimates sediment thickness of the Holocene reef deposit along the Florida Keys reef tract.

We estimated the sediment volume of the Holocene reef and sediment deposit that existed at the Lower Florida Keys study site in 1938 by calculating the sediment thickness between the elevation of the Pleistocene bedrock surface and the elevation of the 1938 seafloor surface. We created a DEM for the Lower Florida Keys historical hydrographic data from 1938 using the Delaunay triangulation method described in Section 2.8. We transformed the horizontal datum of the DPB surface map to match that of the 1938 DEM then clipped the area of the DPB surface map to match the area of the LFK study site. We

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converted the depth polygons of the DPB surface map to elevations by assigning XYZ coordinates to them and converting the DPB vertical datums to match those of the 1938 DEM. We then performed a difference analysis between the 1938 DEM surface and the updated DPB elevation layer. We calculated a Holocene reef deposit volume in 1938 of 101.2 Mm³ at the LFK site (see Supplemental Methods Section 1.9 for data processing steps). Comparison of total Holocene reef-deposit volume in 1938 to the amount of net volume loss that occurred between 1938 and 2004 at the study site of 5.7 mM³ (Table 8) indicates that Holocene reef-deposit volume has decreased by as much as 5% over the past 66 years. Assuming a modern reef age of 6000 years (Lidz, 2000) and a constant erosion rate of 5% per 66 years, total reef volume at this location could completely erode down to the Pleistocene-bedrock-surface in approximately 1250 years. This suggests that the Holocene reef deposit may be eroding up to 5 times faster than it accreted throughout the Holocene in the LFK.

The seafloor elevation and volume losses observed in our study indicate the extent of erosion that has already occurred in many coral reef ecosystems may be largely under-estimated without comprehensive analysis of total elevation and volume change. Without such analyses, assessments of risk levels and impact from coastal hazards due to coral reef degradation may also be under-estimated. Numerical models indicate that loss of reef structure and seafloor-elevation increases coastal vulnerability to erosion, storm surge, waves, sea level rise and tsunami hazards that are predicted to intensify and become more frequent with global climate change (Lowe et al., 2005; Quataert et al., 2015). An increase in water depth of 0.5 to 1.0 m from rising sea level by 2100 is projected to cause larger waves and accelerated physical erosion of sediments on fringing reef flats and adjacent coastlines (Storlazzi et al., 2011). Our results show that degradation of coral reef ecosystems in Atlantic, Caribbean and Pacific regions has accelerated the relative increase in water depth from sea level rise, and has already increased water depths to levels that were not expected until near 2100. We projected increases in water depth at our study sites based on our measured rates of mean elevation loss combined with sea level rise. Our projections indicate that seafloor erosion will increase water depths by 2 to 8 times more than levels predicted from sea level rise alone by the year 2100 at all study sites (Fig. 11, Table S6). This divergence between rising sea level and declining seafloor elevation has already increased the risk to coastlines in these regions from long-term, persistent oceanographic pressures and periodic events such as storms. The combination of human impacts to reefs and unprecedented rates of global climate change are likely to intensify coastal hazard vulnerabilities caused by seafloor erosion in coral reef ecosystems over the next century.

5 Conclusions

Results of our study show that ecosystem- to regional-scale elevation-change analyses are an effective means for quantifying whole system accretion and erosion, and for characterizing change in the physical structure of the seafloor at spatial resolutions needed for numerical modelling of physical oceanographic processes. Furthermore, results from these analyses are valuable for examining the relative contribution of erosion and accretion processes and identifying missing gaps in process accounting. We suggest that combining comprehensive elevation-change analyses with coordinated ecosystem

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process studies and appropriately scaled geologic characterization can better establish the links among contemporary processes causing coral reef ecosystem degradation, long-term changes in the physical structure of the environment, and future implications for physical and societal impacts. There are, however, some key limitations that should be considered in future applications of these methods including:

- 1) Elevation-change analyses alone do not attribute physical change in seafloor structure to cause, but can be combined with results from field observations and process studies to help identify and account for the causes.
- 2) Calculation of accretion and erosion from these methods is limited to volumetric values and cannot be used to determine mass of carbonate without more detailed analysis of sediment and materials bulk densities.
- 3) Not all historical or contemporary bathymetric data sets are appropriate for use in these studies. The coarse horizontal resolution of most historical data limits assessments to large spatial scales. Careful evaluation of the potential error due to data resolution must be performed.

The findings of our study show that coral reef ecosystems in the Florida Keys, U.S. Virgin Islands and Maui, Hawaii are net erosional. Elevation and volume losses observed in our study indicate the amount of erosion that has occurred over the past several decades has likely been underestimated in previous studies. Substantial erosion was observed both in coral-dominated and non-coral dominated habitats. However, erosion in non-coral habitats accounted for most of the volume loss at these study sites suggesting that carbonate production at these sites can no longer support accretion of coral reefs or their adjacent habitats. Select habitats that were more distant from large population centers, or were located in protected areas or near refuges, showed either lower rates of erosion or net accretion illustrating the value of managed protection in these areas. However, those areas showing net accretion could not compensate for ecosystem-scale, mean-loss trends. The magnitude of reef volume lost due to erosion provides evidence for the onset of an Anthropocene reef crisis similar to ancient reef crises caused by climate change and marked in the geologic record by regional and global declines in reef volume. Losses in mean seafloor elevation over the past few decades have already increased local sea level rise to water depths not predicted to occur until near 2100, and to levels that exacerbate impacts of coastal erosion, storm surge, waves, and tsunami hazards. The magnitude of erosion that has already occurred, trajectories for continued coral reef degradation and increasing sea level place these ecosystems and nearby communities at elevated and accelerating risk to coastal hazards.

Author contributions

K.K. Yates and D.G. Zawada conceived of and designed the research project, interpreted the results, and wrote the manuscript. N.A. Smiley acquired and processed the historical data sets. G. Tiling-Range created the ArcGIS models to automate computation of the habitat-related statistics.

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Table 1 Area, benthic cover and fish survey statistics for study sites.

Location	Study site area (km ²)	Δ % live coral	Δ % macroalgae	Δ <i>Diadema</i> sp. density (# m ⁻²)	Δ parrotfish biomass (g m ⁻²)
UFK	241.1	-23 (1975 – 2011)	+15 (1974 – 2011)	-2 (density near 0) (1970's – 2011)	+5 (late 1990's – 2011)
LFK	19.0	-25 (1984 – 2010)	+15 (1974 – 2011)	-3 to -17 (1970's – 2011)	+5 (late 1990's – 2011)
STT	116.9	-10 (1978 – 2011)	+5 (2001 – 2010)	-23 (1973 – 2011)	+13 (2008 – 2010)
BI	51.8	-14 (1976 – 2011)	0 (1982 – 2011)	-23 (1973 – 2011)	-2 (2003 – 2010)
Maui	84.5	-4 (1999 – 2015)	Decrease (1999 – 2015)	N	0 to increase (2008 – 2015)

Values are estimated from data reported in Jackson et al. (2014) and Sparks et al. (2015). N = no data. Parentheses indicate time period of data collection.

Table 2. Population at study sites.

<u>Study region</u>	<u>Census Date</u>	<u>Population</u>
Florida Keys (Monroe County)	1940	14078
Florida Keys	2000	79535
Key Largo, Upper Florida Keys	2000	12971
Key West, Lower Florida Keys	2000	25431
St. Thomas, US Virgin Islands	1970	28960
	2010	51634
Buck Island, US Virgin Islands	1980	Uninhabited
	2010	Uninhabited (50,000 visitors/yr)
Maui, Hawaii	1960	35717
	2000	117644

Notes. Data acquired from the U.S. Census Bureau (2016).

Table 3. Bathymetric and habitat data sources and descriptions.

<u>Study site</u>	<u>Data type</u>	<u>Source</u>	<u>Source reference</u>	<u>Source title</u>	<u>Year</u>
U FK (68 yrs)	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H05536	1934
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H05578	1934
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H05726A	1934
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H05878A	1935
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H05879	1935
	LiDAR	USGS	(Brock et al., 2007; Brock et al., 2006a)	EAARL	2002
	Habitat	FWC	(Florida Fish and Wildlife Conservation Commission, 2015)	UFRT Habitat Map v1.2	2014
L FK (66 yrs)	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H06323	1938
	LiDAR	USAC	(U.S. Army Corps of Engineers-JALBTCX, 2004)	SHOALS	2004
	Habitat	FWC	(Florida Fish and Wildlife Conservation Commission, 2015)	UFRT Habitat Map v1.2	2014
S TT (48 yrs)	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H08877	1966
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H09271	1972
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H09272	1972
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H09353	1973
	LiDAR	USGS	(Fredericks et al., 2015b)	EAARL	2014
	Habitat	NOAA	(Kendall, 2001a)	NOAA	1999
S TC (33 yrs)	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H09936	1981
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H10002	1982
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H10003	1982
	LiDAR	USGS	(Fredericks et al., 2015a)	EAARL	2014
	Habitat	NOAA	(Kendall, 2001b)	NOAA	1999
M aui (38 yrs)	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H08576	1961
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H08577	1961
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H08578	1961
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H08579	1961
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H08580	1961
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H08581	1961
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H08680	1962
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H08681	1963
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H08682	1962
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H08683	1962
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H08684	1962
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H08685	1962
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H08686	1962
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H08687	1962
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H08717	1963
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H08718	1966
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H08719	1965
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H08720	1963
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H08721	1963
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H08723	1963
	Bathymetry	NOAA	(NOAA Office of Coast Survey)	H08792	1964

<u>Bathymetry</u>	<u>NOAA</u>	<u>(NOAA Office of Coast Survey)</u>	<u>H08793</u>	<u>1964</u>
<u>Bathymetry</u>	<u>NOAA</u>	<u>(NOAA Office of Coast Survey)</u>	<u>H08825</u>	<u>1965</u>
<u>Bathymetry</u>	<u>NOAA</u>	<u>(NOAA Office of Coast Survey)</u>	<u>H08826</u>	<u>1965</u>
<u>LiDAR</u>	<u>USAC</u>	<u>(U.S. Army Corps of Engineers-</u>	<u>SHOALS</u>	<u>1999</u>
	<u>E</u>	<u>JALBTCX, 1999)</u>		
<u>Habitat</u>	<u>NOAA</u>	<u>(Battista and Christensen, 2007)</u>	<u>NOAA</u>	<u>2007</u>

Table 4. Geospatial information and transformations for historical bathymetry and LiDAR data.

Study region	Source title	Vertical datum source	Geoid	Vertical datum final	Geoid	Horizontal datum source	UTM zone	Horizontal datum final	UTM zone	NOAA sea level trend station	NOAA sea-level rise rate (mm/yr)	Yrs	Relative sea-level rise correction (m)
UFK	H05536	MLW	-	NAVD88	03	Geo NAD83	-	UTM NAD83	17	8724580	2.33	67	0.15611
	H05578	MLW	-	NAVD88	03	Geo NAD83	-	UTM NAD83	17	8724580	2.33	67	0.15611
	H05726A	MLW	-	NAVD88	03	Geo NAD83	-	UTM NAD83	17	8724580	2.33	67	0.15611
	H05878A	MLW	-	NAVD88	03	Geo NAD83	-	UTM NAD83	17	8724580	2.33	66	0.15378
	H05879	MLW	-	NAVD88	03	Geo NAD83	-	UTM NAD83	17	8724580	2.33	66	0.15378
	EAARL	NAVD88	03	NAVD88	03	Geo NAD83	-	UTM NAD83	17	-	-	-	-
LFK	H06323	MLW	-	NAVD88	03	Geo NAD83	-	UTM NAD83	17	8724580	2.33	66	0.15378
	SHOALS	NAVD88	03	NAVD88	03	UTM NAD83	17	UTM NAD83	17	-	-	-	-
STT	H08877	MLLW	-	VIVD09	-	Geo NAD83	-	UTM NAD83	20	9751639	1.77	48	0.08496
	H09271	MLLW	-	VIVD09	-	Geo NAD83	-	UTM NAD83	20	9751639	1.77	42	0.07434
	H09272	MLLW	-	VIVD09	-	Geo NAD83	-	UTM NAD83	20	9751639	1.77	42	0.07434
	H09353	MLLW	-	VIVD09	-	Geo NAD83	-	UTM NAD83	20	9751639	1.77	41	0.07257
	EAARL	NAVD88	12B	NAVD88	12B	UTM NAD83	20	UTM NAD83	20	-	-	-	-
STC	H09936	MLLW	-	VIVD09	-	Geo NAD83	-	UTM NAD83	20	9751401	2.29	33	0.07557
	H10002	MLLW	-	VIVD09	-	Geo NAD83	-	UTM NAD83	20	9751401	2.29	32	0.07328
	H10003	MLLW	-	VIVD09	-	Geo NAD83	-	UTM NAD83	20	9751401	2.29	32	0.07328
	EAARL	NAVD88	12B	NAVD88	12B	UTM NAD83	20	UTM NAD83	20	-	-	-	-
Maui	H08576	MLLW	-	MLLW	-	Geo NAD83	-	UTM NAD83	4	1615680	2.02	38	0.07676
	H08577	MLLW	-	MLLW	-	Geo NAD83	-	UTM NAD83	4	1615680	2.02	38	0.07676
	H08578	MLLW	-	MLLW	-	Geo NAD83	-	UTM NAD83	4	1615680	2.02	38	0.07676
	H08579	MLLW	-	MLLW	-	Geo NAD83	-	UTM NAD83	4	1615680	2.02	38	0.07676
	H08580	MLLW	-	MLLW	-	Geo NAD83	-	UTM NAD83	4	1615680	2.02	38	0.07676
	H08581	MLLW	-	MLLW	-	Geo NAD83	-	UTM NAD83	4	1615680	2.02	38	0.07676
	H08680	MLLW	-	MLLW	-	Geo NAD83	-	UTM NAD83	4	1615680	2.02	37	0.07474
	H08681	MLLW	-	MLLW	-	Geo NAD83	-	UTM NAD83	4	1615680	2.02	36	0.07272
	H08682	MLLW	-	MLLW	-	Geo NAD83	-	UTM NAD83	4	1615680	2.02	37	0.07474
	H08683	MLLW	-	MLLW	-	Geo NAD83	-	UTM NAD83	4	1615680	2.02	37	0.07474
	H08684	MLLW	-	MLLW	-	Geo NAD83	-	UTM NAD83	4	1615680	2.02	37	0.07474
	H08685	MLLW	-	MLLW	-	Geo NAD83	-	UTM NAD83	4	1615680	2.02	37	0.07474
	H08686	MLLW	-	MLLW	-	Geo NAD83	-	UTM NAD83	4	1615680	2.02	37	0.07474
	H08687	MLLW	-	MLLW	-	Geo NAD83	-	UTM NAD83	4	1615680	2.02	37	0.07474
	H08717	MLLW	-	MLLW	-	Geo NAD83	-	UTM NAD83	4	1615680	2.02	36	0.07272
	H08718	MLLW	-	MLLW	-	Geo NAD83	-	UTM NAD83	4	1615680	2.02	33	0.06666
	H08719	MLLW	-	MLLW	-	Geo NAD83	-	UTM NAD83	4	1615680	2.02	34	0.06868
	H08720	MLLW	-	MLLW	-	Geo NAD83	-	UTM NAD83	4	1615680	2.02	36	0.07272
	H08721	MLLW	-	MLLW	-	Geo NAD83	-	UTM NAD83	4	1615680	2.02	36	0.07272
	H08723	MLLW	-	MLLW	-	Geo NAD83	-	UTM NAD83	4	1615680	2.02	36	0.07272
H08792	MLLW	-	MLLW	-	Geo NAD83	-	UTM NAD83	4	1615680	2.02	35	0.0707	
H08793	MLLW	-	MLLW	-	Geo NAD83	-	UTM NAD83	4	1615680	2.02	35	0.0707	
H08825	MLLW	-	MLLW	-	Geo NAD83	-	UTM NAD83	4	1615680	2.02	34	0.06868	
H08826	MLLW	-	MLLW	-	Geo NAD83	-	UTM NAD83	4	1615680	2.02	34	0.06868	
SHOALS	MLLW	-	MLLW	-	UTM NAD83	4	UTM NAD83	4	-	-	-	-	-

Notes: Dashes indicate not applicable. Years = number of years by which sea-level rise rates were multiplied to calculate relative sea-level rise correction.

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Table 5. Vertical error analysis results.

Study site	Historical Data			Modern Data	VDatum	Study Site Totals	
	# paired points	RMSE _{Sound} mg (m)	T-test results (± P)	RMSE _{Lidar} (m)	RMSE _{VDat} (m)	RMSE _{Total} (m)	*1.65 x study site RMSE _{Total} (m)
LFK	38	0.23	± 0.96	0.15	0.081	0.29	0.47
STT	184	0.26	± 0.81	0.135	0.114	0.31	0.52
STC	29	0.32	± 0.93	0.135	0.114	0.37	0.60
Maui	46	0.13	± 0.99	0.15		0.20	0.33
Average						0.29	0.48

Notes: LFK was excluded from the error analysis because no adjacent points were separated by 0.5 m or less. For t-test results, + = accept H₀. *1.65 x study site RMSE_{Total} = 90% of variance.

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Table 6. Results of pavement elevation-data analysis.

<u>Study site</u>	<u>Total # habitat data points</u>	<u># Points within +/- 0.5 m elevation change</u>	<u>Average difference (m)</u>	<u>Stdev.</u>
UFK - pavement	1901	958	-0.06	0.27
LFK - pavement	198	34	-0.03	0.1
STT – uncolonized pavement	33	28	-0.04	0.2
BI – colonized pavement	3286	2543	0.04	0.26
Maui – coral pavement	4412	1013	0.05	0.14

Average elevation differences between modern and historical elevation data (modern – historical) and standard deviation (Stdev.) are reported for those data points elevation changes within +/- 0.5 m (or $1.65 \times \text{RMSE}_{\text{Total}}$).

Table 7. Horizontal shift analysis results.

Study site & relative location	Net volume change (Mm ³)	% difference from un-shifted value	Area-normalized volume change (Mm ³ /km ²)	% difference from un-shifted value
UFK				
Un-shifted	-37.9	-	-0.16	-
x + 10 m	-41.7	10	-0.17	6
x - 10 m	-34.9	8	-0.15	6
y + 10 m	-36.6	3	-0.15	6
y - 10 m	-39.5	4	-0.16	0
LFK				
Un-shifted	-5.7	-	-0.30	-
x + 10 m	-5.8	2	-0.31	3
x - 10 m	-5.4	5	-0.29	3
y + 10 m	-4.5	21	-0.24	20
y - 10 m	-6.7	18	-0.35	17

Un-shifted results are derived from the original point to DEM data sets, correctly aligned to horizontal datums, for each study site. Experimental data sets were created by shifting UTM northings and eastings of historical elevation XYZ data sets by plus or minus 10 m and recalculating volume change relative to unshifted LiDAR elevation data.

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Table 8. Seafloor elevation and volume change for Atlantic, Pacific and Caribbean study sites.

Location, time period	Study area (km ²)	Mean elevation change (m)	Standard deviation (m)	Gross erosion (Mm ³)		Gross accretion (Mm ³)		Net volume change (Mm ³)		Area-normalized volume change (Mm ³ /km ²)	
				Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
UFK, 1934/35-2002	241.1	-0.1	0.8	-22.2	-69.9	7.5	32.1	-14.6	-37.9	-0.06	-0.2
LFK, 1938-2004	19.0	-0.3	0.8	-1.8	-8.2	1.6	2.6	-0.2	-5.7	-0.01	-0.3
STT, 1966/73-2014	116.9	-0.3	0.9	-7.4	-29.1	1.4	7.5	-6.0	-21.6	-0.05	-0.2
BI, 1981/82-2014	51.8	-0.09	0.7	-2.3	-9.6	0.7	6.1	-1.6	-3.4	-0.03	-0.07
Maui, 1961/65-1999	84.5	-0.8	1.5	-56.6	-88.5	3.2	7.2	-52.8	-80.5	-0.6	-0.9
UFK coral habitats (5)	36.1	-0.2	1.1	-5.9	-14.3	2.3	6.3	-3.5	-7.9	-0.1	-0.2
UFK adjacent habitats	204.9	-0.1	-0.7	-15.6	-54.9	4.8	25.0	-10.8	-30	-0.05	-0.15
LFK coral habitats (4)	1.6	0.2	1.4	-0.1	-0.4	0.9	1.3	0.8	0.9	0.50	0.55
LFK adjacent habitats	17.3	-0.4	0.6	-1.6	-7.8	0.7	1.3	-1.0	-6.5	-0.06	-0.40
STT coral habitats (9)	14.3	-0.5	1.3	-4.0	-7.9	0.6	1.7	-3.4	-6.2	-0.2	-0.4
STT adjacent habitats	102.7	-0.2	0.6	-3.3	-21.2	0.7	5.8	-2.6	-15.4	-0.03	-0.2
BI coral habitats (7)	47.1	-0.09	0.72	-2.0	-8.7	0.6	5.6	-1.4	-3.1	-0.03	-0.07
BI adjacent habitats	4.7	-0.09	0.68	-0.3	-0.9	0.1	0.6	-0.2	-0.3	-0.05	-0.07
Maui coral habitats (7)	48.4	-0.9	1.5	-32.2	-50.0	1.9	4.2	-30.4	-45.8	-0.6	-0.9
Maui adjacent habitats	36.2	-0.8	1.5	-23.5	-37.3	1.1	2.6	-22.4	-34.7	-0.6	-1.0

Minimum (Min.) and maximum (Max.) volumes are based on vertical error analysis (Table 5). Parenthetical numbers indicate number of combined habitat classes for each location (Tables 9 and 10). Mm³ = millions of cubic meters.

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Table 9. Elevation change by habitat type.

Location	Mean elevation (m)	Total points (#)	Mean elevation change (m)	Stdev (m)	Max loss (m)	Max gain (m)	Elevation loss points (#)	Mean loss (m)	Stdev (m)	Elevation gain points (#)	Mean gain (m)	Stdev (m)
Upper Florida Keys												
Total study site	-6.7	2634	-0.1	0.8	-8.3	6.5	14996	-0.6	0.7	11345	0.44	0.51
*Scattered coral/rock in uncons. sed.	-6.9	17	-0.8	0.9	-2.0	1.2	13	-1.1	0.6	4	0.5	0.4
Pavement	-5.9	1901	-0.2	1.0	-6.2	4.9	1218	-0.7	0.7	683	0.7	0.7
*Aggregate reef	-6.6	1435	-0.2	1.1	-5.1	4.7	857	-0.8	0.8	578	0.7	0.7
*Reef rubble	-3.6	291	-0.2	0.8	-2.6	3.2	196	-0.6	0.5	95	0.6	0.7
Unconsolidated sediments	-8.7	5498	-0.2	0.6	-6.8	3.4	3526	-0.5	0.5	1972	0.3	0.3
*Individual or aggregate patch reef	-5.8	2078	-0.2	1.1	-6.6	5.2	1170	-0.8	0.9	908	0.6	0.7
Seagrass continuous	-6.7	6826	-0.2	0.8	-8.0	3.2	3604	-0.6	0.8	3322	0.4	0.3
Seagrass discontinuous	-5.2	6944	-0.1	0.5	-8.3	2.6	3721	-0.4	0.4	3223	0.3	0.3
*Spur and groove	-8.7	613	-0.02	1.3	-4.6	6.5	343	-0.8	0.8	270	1.0	1.0
Pavement w/sand channels	-12.1	623	0.2	1.2	-3.2	5.7	313	-0.8	0.7	310	1.1	0.9
Not classified	-6.2	113	0.2	0.5	-2.0	2.0	34	-0.4	0.4	79	0.4	0.3
Lower Florida Keys, Looe Key												
Total study site	-8.7	1688	-0.3	0.8	-4.0	7.3	1361	-0.6	0.4	327	0.7	1.1
*Individual or aggregate patch reef	-10.1	14	-0.8	0.8	-3.5	-0.2	14	-0.8	0.8	-	-	-
*Reef rubble	-4.7	68	-0.7	0.8	-2.9	0.9	55	-0.9	0.6	13	0.3	0.3
Seagrass continuous	-8.6	285	-0.5	0.4	-3.1	0.4	264	-0.5	0.3	21	0.2	0.1
Seagrass discontinuous	-7.4	488	-0.5	0.5	-1.9	2.0	427	-0.6	0.3	61	0.3	0.3
Pavement	-9.4	198	-0.4	0.7	-2.2	1.9	151	-0.6	0.4	47	0.5	0.5
Unconsolidated sediments	-9.8	533	-0.4	0.7	-4.0	6.3	428	-0.6	0.4	105	0.7	1.0
*Spur and groove	-9.3	68	0.5	1.1	-1.4	4.2	21	-0.5	0.4	47	1.0	1.0
*Aggregate reef	-15.1	29	2.0	1.9	-1.4	7.3	1	-1.4	0.0	28	2.2	1.9
Not classified	-19.8	5	3.0	1.3	0.7	4.1	-	-	-	5	2.9	1.3
St. Thomas, US Virgin Islands												
Total study site	-18.6	4926	-0.3	0.9	-	25.6	35332	-0.5	0.7	13937	0.4	0.9
*Spur and groove	-7.3	75	-1.1	1.6	-5.9	3.1	60	-1.6	1.2	15	1.1	0.9
*Patch reef (aggregate)	-19.9	163	-1.0	1.6	-5.9	4.9	138	-1.3	1.4	25	0.9	1.2
*Linear reef	-15.7	2244	-0.7	1.5	-	7.0	1632	-1.2	1.4	612	0.7	0.8
												11.2
*Colonized bedrock	-5.7	1968	-0.6	1.5	-8.3	6.1	1358	-1.2	1.2	610	0.9	1.0
*Colonized pave.w/sand channels	-17.0	591	-0.5	1.0	-5.7	4.3	438	-0.9	0.8	153	0.5	0.6
Uncolonized pave. w/sand channels	-11.5	41	-0.5	0.9	-3.0	0.9	27	-0.9	0.9	14	0.3	0.3
Mud	-8.3	1857	-0.5	1.1	-5.6	3.4	1262	-1.0	0.9	595	0.5	0.5
*Scattered coral/rock in uncons. sed.	-11.4	324	-0.5	1.3	-8.4	4.3	228	-0.9	1.2	96	0.5	0.7
*Colonized pavement	-11.5	3195	-0.4	1.0	-7.9	8.1	2249	-0.8	0.9	946	0.5	0.6
*Patch reef (individual)	-19.0	280	-0.3	1.1	-5.3	3.2	193	-0.8	0.8	87	0.7	0.8
Seagrass	-12.6	1111	-0.2	0.6	-7.5	13.2	7914	-0.4	0.6	3199	0.3	0.5
		3										
Macroalgae	-23.4	1397	-0.2	0.5	-	4.0	10360	-0.3	0.5	3613	0.2	0.2
		3										11.1
Sand	-8.6	961	-0.2	0.8	-4.2	3.9	571	-0.6	0.6	390	0.4	0.5
Unknown	-25.6	1199	-0.2	0.6	-8.6	11.5	8533	-0.3	0.5	3459	0.2	0.5
		2										
*Reef rubble	0.6	1	-0.1	0	-0.1	-	1	-0.1	0	-	-	-
Uncolonized pavement	-10.6	33	-0.1	0.4	-1.2	0.7	20	-0.3	0.4	13	0.2	0.2
Uncolonized bedrock	-1.9	6	1.1	1.0	-	2.3	-	-	-	6	1.1	1.0
Buck Island, US Virgin Islands												

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Total study site	-17.9	1389	0.1	0.7	-8.6	6.8	7200	-0.5	0.7	6694	0.4	0.4
*Patch reef (aggregated)	-11.4	1086	-0.5	1.5	-8.6	6.8	629	-1.3	1.5	457	0.5	0.9
*Patch reef (individual)	-15.5	17	-0.3	0.5	-1.5	0.7	13	-0.5	0.4	4	0.3	0.3
Unknown	-29.7	551	-0.3	0.9	-4.9	3.5	326	-0.8	0.8	225	0.5	0.5
*Colonized pave./w sand channels	-18.7	6914	-0.1	0.6	-5.9	3.3	3809	-0.4	0.5	3105	0.3	0.3
*Scattered coral/rock in unconcons. sed.	-21.1	1152	-0.01	0.6	-4.7	2.8	490	-0.4	0.6	662	0.3	0.3
*Reef rubble	-12.2	10	0	0.3	-0.5	0.5	5	-0.3	0.2	5	0.3	0.2
*Colonized pavement	-16.4	3286	0.01	0.5	-3.0	4.5	1529	-0.4	0.4	1757	0.3	0.3
Seagrass	-14.3	610	0.02	0.4	-2.2	0.9	270	-0.2	0.3	340	0.2	0.2
Sand	-15.3	88	0.1	0.6	-3.8	0.9	27	-0.5	0.8	61	0.3	0.2
Macroalgae	-10.0	26	0.2	0.5	-1.6	0.7	4	-0.6	0.7	22	0.3	0.2
*Linear reef	0.1	83	0.6	2.1	-3.0	5.7	43	-0.9	0.8	40	2.2	1.9
Maui, Hawaii												
Total study site	-17.0	2751	-0.8	1.5	-	11.8	22111	-1.2	1.4	5407	0.7	0.9
		8				28.7						
*Individual patch reef	-14.1	166	-1.3	2.0	-7.4	4.9	140	-1.9	1.5	26	1.6	1.3
*Coral reef and hardbottom	-12.4	5610	-1.3	2.0	-	8.3	4592	-1.8	1.8	1018	1.0	1.2
						16.7						
Unknown	-12.1	4548	-1.2	2.2	-	9.2	3520	-1.8	2.1	1028	0.8	1.0
						28.7						
*Spur and groove	-8.2	369	-0.8	1.1	-9.2	2.7	300	-1.1	1.0	69	0.5	0.5
*Aggregate patch reef	-14.5	170	-0.7	0.8	-3.9	1.7	148	-0.9	0.7	22	0.6	0.5
*Aggregate reef	-10.1	3666	-0.7	1.1	-9.4	8.6	2892	-1.0	0.9	774	0.6	0.8
Sand	-13.6	8381	-0.6	0.8	-	9.8	7272	-0.8	0.7	1109	0.5	0.7
						11.5						
*Scattered coral/rock	-4.0	17	-0.6	0.7	-2.1	0.9	15	-0.7	0.5	2	0.7	0.3
*Coral pavement	-9.3	4412	-0.4	0.9	-	6.4	3120	-0.8	0.8	1292	0.5	0.6
						10.4						
Pavement w/sand channels	-13.8	158	-0.4	0.9	-4.3	1.8	105	-0.8	0.8	53	0.5	0.4
Rubble	-2.6	10	0.03	0.5	-0.5	0.8	5	-0.4	0.1	5	0.5	0.3
Mud	-2.2	4	0.2	1.3	-0.6	2.1	3	-0.4	0.2	1	2.1	0.0
Notes: * = coral-dominated substrate. Uncons. sed. = unconsolidated sediment. Pave. = pavement. /w = with. Mean elevations are based on LIDAR bathymetry. Dashes indicate not applicable. Data points were excluded from habitat analysis where no habitat delineations were available. Total study site values include all data points.												

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Table 10. Volume change by habitat type

Location	Habitat area (km ²)	Gross erosion (Mm ³)		Gross accretion (Mm ³)		Net volume change (Mm ³ /study area)		Area-normalized volume change (Mm ³ /km ²)	
		Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
		Upper Florida Keys							
Total study site	241.1	-21.5	-69.2	7.1	31.3	-14.3	-37.9	-0.1	-0.2
*Scattered coral/rock in uncons. sed.	0.2	-0.1	-0.1	0.00	0.01	-0.1	-0.1	-0.3	-0.7
Pavement	17.0	-2.4	-6.6	0.8	2.4	-1.6	-4.3	-0.1	-0.3
*Aggregate reef	11.8	-1.9	-4.5	0.8	2.3	-1.1	-2.2	-0.1	-0.2
*Reef rubble	1.5	-0.2	-0.6	0.1	0.2	-0.1	-0.4	-0.1	-0.2
Unconsolidated sediments	65.3	-4.1	-17.5	0.9	5.8	-3.2	-11.7	-0.05	-0.2
*Individual or aggregate patch reef	17.2	-2.9	-7.1	0.6	2.1	-2.4	-4.9	-0.1	-0.3
Seagrass continuous	63.5	-6.4	-18.7	1.1	8.5	-5.2	-10.2	-0.1	-0.2
Seagrass discontinuous	51.9	-2.0	-9.8	0.7	6.0	-1.3	-3.9	-0.02	-0.1
*Spur and groove	5.5	-0.8	-2.0	0.8	1.6	0.1	-0.3	0.01	-0.1
Pavement with sand channels	6.3	-0.8	-2.2	1.2	2.2	0.4	-0.04	0.1	-0.01
Not classified	0.7	-0.01	-0.04	0.03	0.2	0.02	0.1	0.03	0.2
Lower Florida Keys, Looe Key									
Total study site	19.0	-1.7	-8.2	1.6	2.6	-0.1	-5.6	-0.01	-0.3
*Individual or aggregate patch reef	0.1	-0.02	-0.1	0.00	0.00	-0.02	-0.1	-0.2	-0.6
*Reef rubble	0.4	-0.1	-0.2	0.00	0.01	-0.1	-0.2	-0.2	-0.5
Seagrass continuous	3.6	-0.2	-1.7	0.00	0.01	-0.2	-1.7	-0.1	-0.5
Seagrass discontinuous	4.6	-0.5	-2.3	0.0	0.1	-0.5	-2.2	-0.1	-0.5
Pavement	2.2	-0.2	-0.9	0.02	0.1	-0.2	-0.8	-0.1	-0.3
Unconsolidated sediments	6.8	-0.7	-2.9	0.5	0.9	-0.2	-2.0	-0.02	-0.3
*Spur and groove	0.7	-0.01	-0.1	0.2	0.4	0.2	0.3	0.3	0.4
*Aggregate reef	0.4	0.00	-0.01	0.7	0.9	0.7	0.9	1.6	2.1
Not classified	0.1	0.00	0.00	0.1	0.2	0.1	0.2	1.7	2.2
St. Thomas, US Virgin Islands									
Total study site	116.9	-7.4	-29.1	1.4	7.5	-6.0	-21.6	-0.05	-0.2
*Spur and groove	0.1	-0.1	-0.2	0.00	0.01	-0.1	-0.2	-0.8	-1.2
*Patch reef (aggregate)	0.4	-0.2	-0.3	0.00	0.02	-0.2	-0.3	-0.4	-0.7
*Linear reef	4.2	-1.3	-2.4	0.2	0.5	-1.1	-1.9	-0.3	-0.5
*Colonized bedrock	2.4	-1.0	-1.8	0.2	0.4	-0.8	-1.3	-0.3	-0.6
*Colonized pavement with sand channels	1.5	-0.3	-0.8	0.02	0.1	-0.3	-0.7	-0.2	-0.5
Uncolonized pavement with sand channels	0.1	0.0	-0.1	0.00	0.01	-0.02	-0.05	-0.2	-0.5
Mud	1.7	-0.6	-1.0	0.1	0.3	-0.5	-0.8	-0.3	-0.5
*Scattered coral/rock in uncons. sed.	0.5	-0.1	-0.2	0.02	0.1	-0.1	-0.1	-0.2	-0.3
*Colonized pavement	4.7	-0.9	-2.0	0.2	0.5	-0.8	-1.5	-0.2	-0.3
*Patch reef (individual)	0.4	-0.1	-0.2	0.02	0.1	-0.1	-0.2	-0.2	-0.4
Seagrass	16.0	-0.9	-3.6	0.1	0.9	-0.7	-2.7	-0.05	-0.2
Macroalgae	44.5	-1.1	-9.8	0.1	1.9	-1.0	-8.0	-0.02	-0.2
Sand	1.6	-0.1	-0.4	0.03	0.1	-0.1	-0.3	-0.1	-0.2
Unknown	38.8	-0.6	-6.2	0.3	2.6	-0.2	-3.6	-0.01	-0.1
*Reef rubble	0.02	0.00	-0.01	0.00	0.00	0.00	-0.01	-0.1	-0.5
Uncolonized pavement	0.1	0.00	-0.01	0.00	0.01	0.00	0.00	-0.02	0.0
Uncolonized bedrock	0.02	0.00	0.00	0.00	0.01	0.00	0.01	0.2	0.3
Buck Island, US Virgin Islands									
Total study site	51.8	-2.3	-9.6	0.7	6.1	-1.6	-3.4	-0.03	-0.07
*Patch reef (aggregated)	3.2	-0.9	-1.6	0.1	0.4	-0.8	-1.2	-0.2	-0.4
*Patch reef (individual)	0.1	0.00	-0.01	0.00	0.00	0.00	-0.01	-0.03	-0.2
Unknown	1.8	-0.2	-0.6	0.05	0.2	-0.2	-0.4	-0.1	-0.2
*Colonized pavement with sand channels	27.3	-0.8	-5.0	0.3	2.9	-0.5	-2.1	-0.02	-0.1
*Scattered coral/rock in uncons. sed.	4.5	-0.1	-0.5	0.00	0.6	-0.1	0.0	-0.01	0.01
*Reef rubble	0.03	0.00	-0.01	0.00	0.00	0.00	0.00	-0.03	-0.1
*Colonized pavement	11.9	-0.2	-1.4	0.1	1.6	-0.02	0.2	0.00	0.01
Seagrass	2.4	-0.03	-0.2	0.00	0.2	-0.02	0.1	-0.01	0.0

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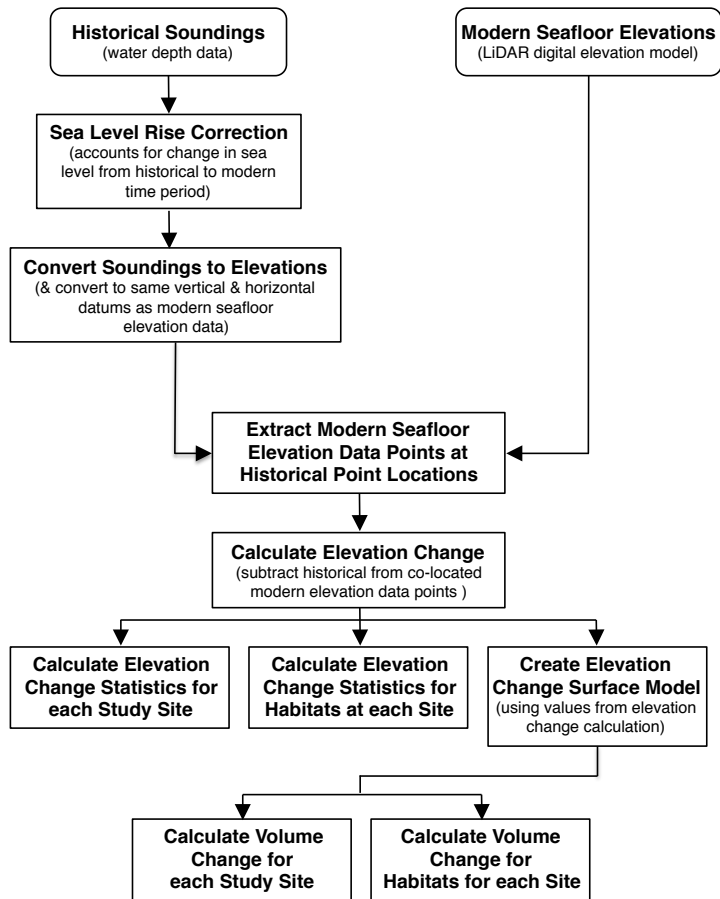


Figure 1. Methods flow diagram for elevation and volume change analysis. Negative values = losses. Positive values = gains. Net volume change = volume loss + volume gain. Using surface models, volume loss = 3D surface volume below 0 m reference; volume gain = 3D surface volume above 0 m reference.

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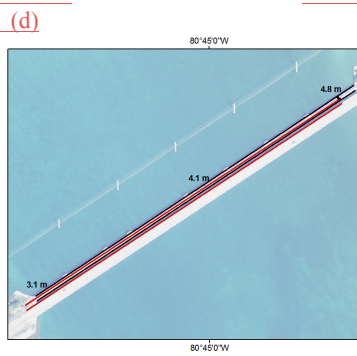
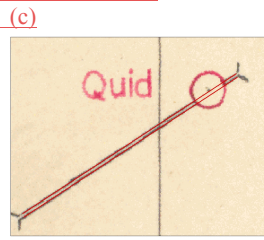
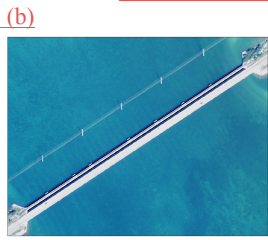


Figure 2. Example of visual inspection of historical Hsheets relative to modern aerial imagery as a preliminary ‘check’ for horizontal alignment. Historical bridge (a) overlay, merging the (b) 2016 aerial imagery with (c) 1934 H-sheet. ArcMap measurement lines (d).

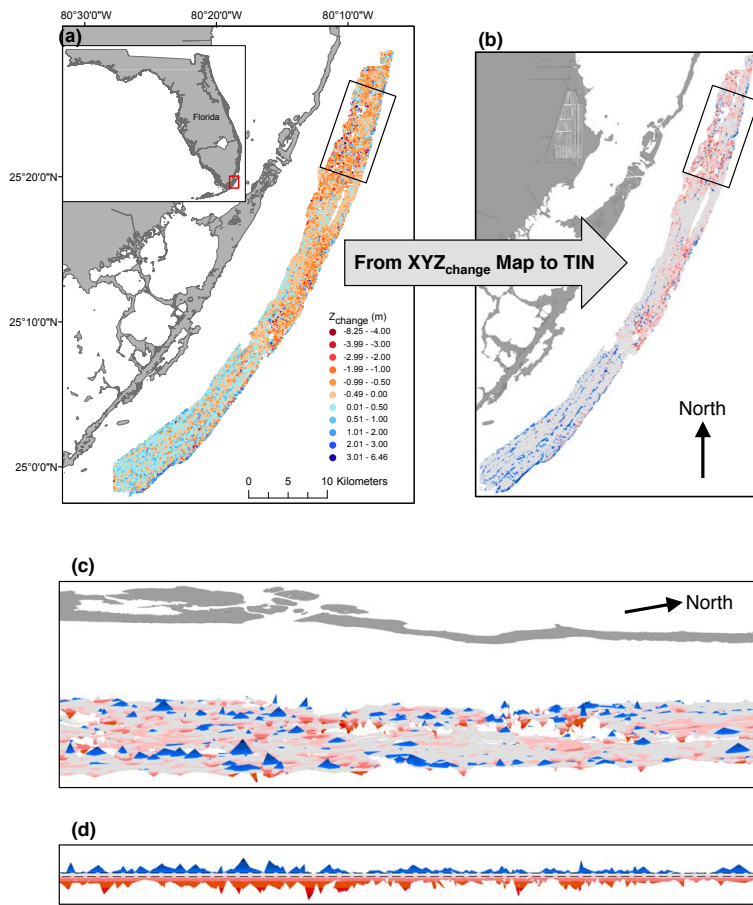
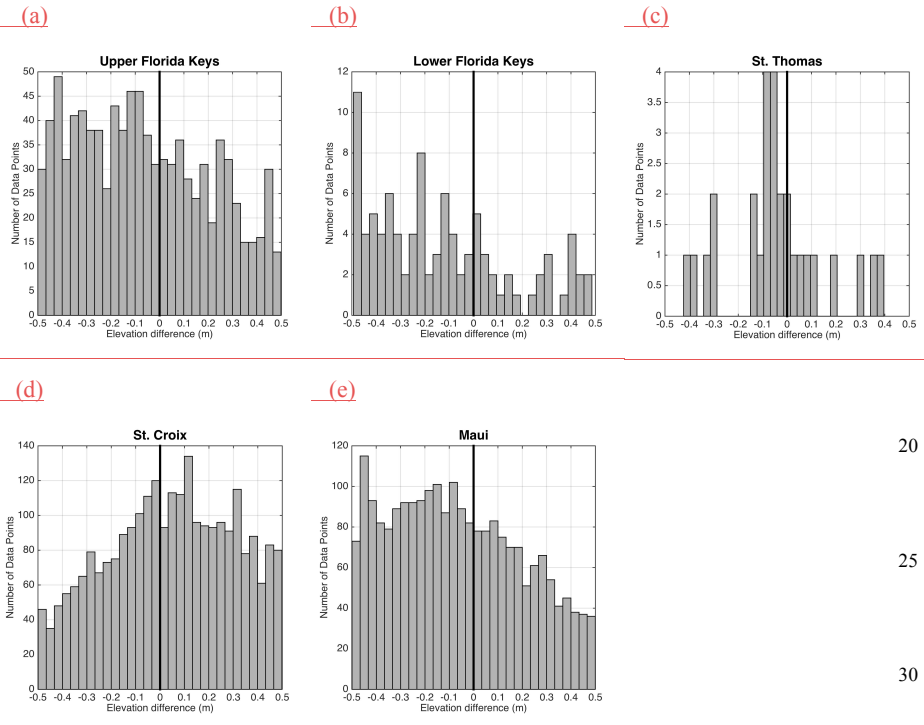


Figure 3. Examples of (a) the XYZ_{change} data plot, (b) the three-dimensional triangulated irregular network (TIN) model developed from the XYZ_{change} data, (c) a sub-section of the TIN model, rectangle in (b), rotated clockwise approximately 90° and tilted 15° from horizontal, and (d) a horizontal cross-section view of the TIN model sub-section for the Upper Florida Keys study site. Gray areas in (b), (c), and (d) and dashed areas in (d) indicate data within $\pm 0.5\text{m}$ elevation change that were removed for minimum volume calculations. Red = elevation loss, blue = elevation gain in (b), (c), and (d).



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Figure 4. Histograms of elevation-change data for pavement analysis of the (a) Upper Florida Keys, (b) Lower Florida Keys, (c) St. Thomas, (d) Buck Island, St. Croix, and (e) Maui study sites.

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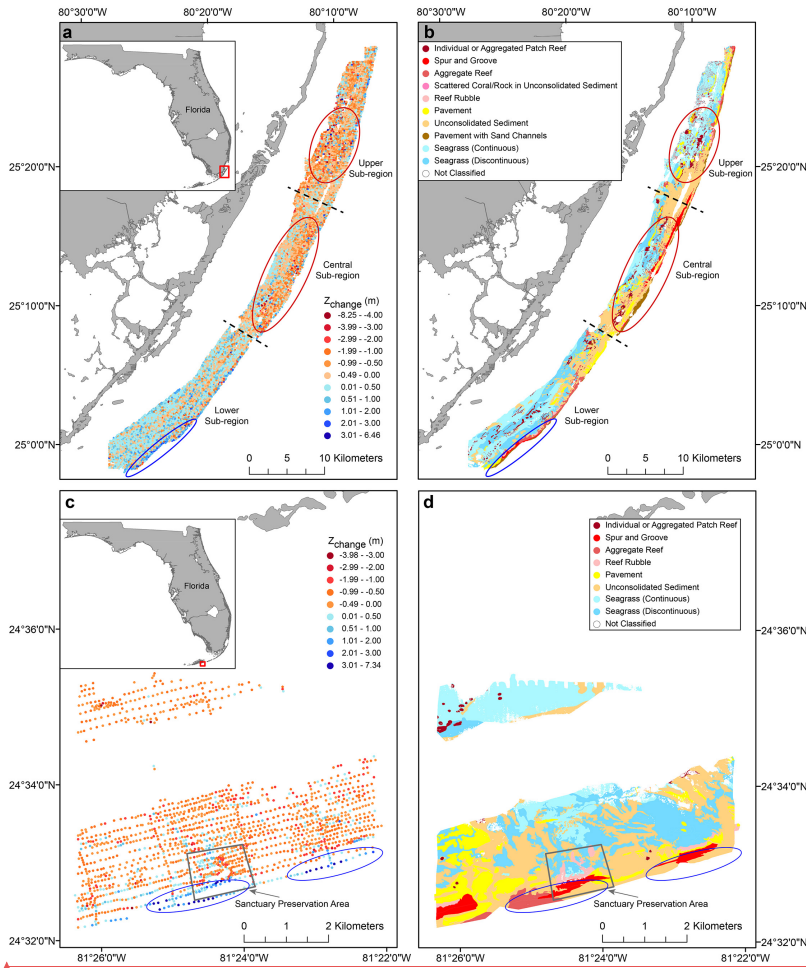


Figure 5. Elevation-change and habitat maps for the Upper Florida Keys (a and b) and Lower Florida Keys (c and d) over 68 and 66 years, respectively. Elevation values are differences in meters between modern and historical elevation data ($Z_{\text{change}} = \text{modern elevation} - \text{historical elevation}$, see Tables [S1](#) and [S2](#)). Negative numbers indicate elevation loss, positive numbers indicate elevation gain. Red and blue circles indicate areas of high erosion and accretion rates, respectively. Dashed lines =

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sub-regions. Habitat maps were modified from existing geo-databases (Table 3).

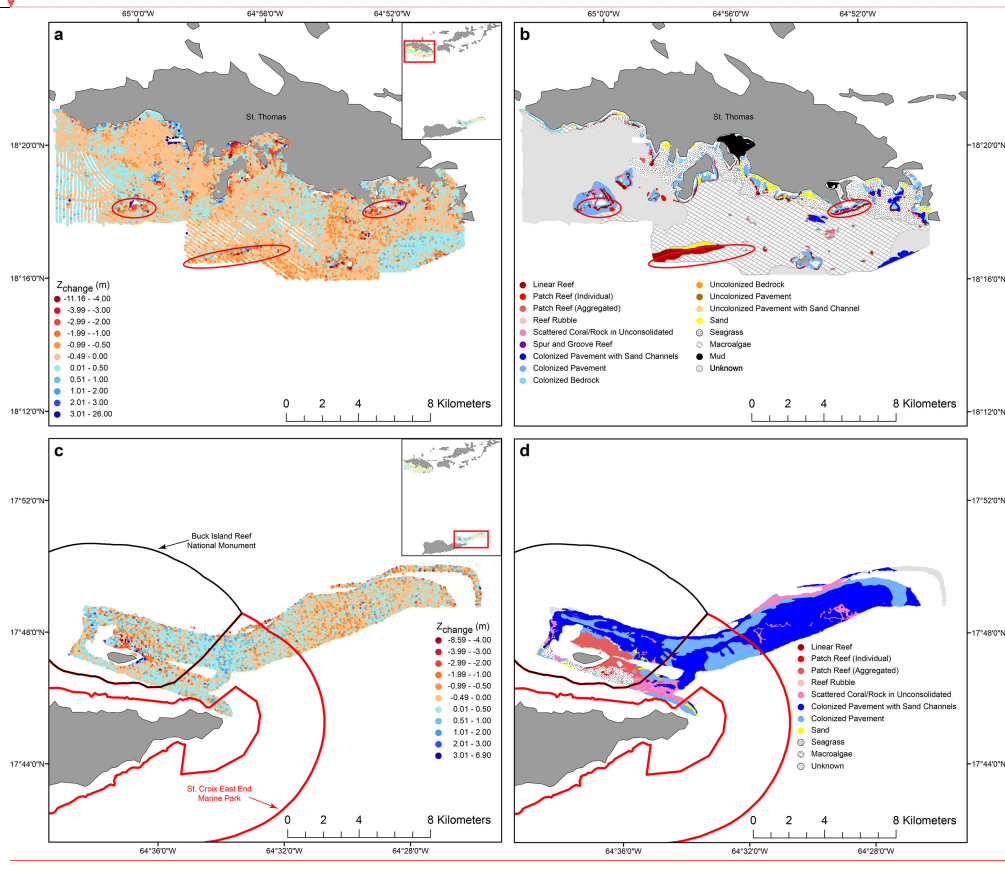


Figure 6. Elevation-change and habitat maps for the U.S. Virgin Islands. St. Thomas elevation-change over 48 years (a) and habitat (b). Buck Island elevation-change over 33 years (c) and habitat (d). Elevation values are differences in meters between modern and historical elevation data ($Z_{\text{change}} = \text{modern elevation} - \text{historical elevation}$, see Tables S3 and S4). Negative numbers indicate elevation loss, positive numbers indicate elevation gain. Red circles indicate areas of high erosion rates. Habitat maps were modified from existing geo-databases (Table 3).

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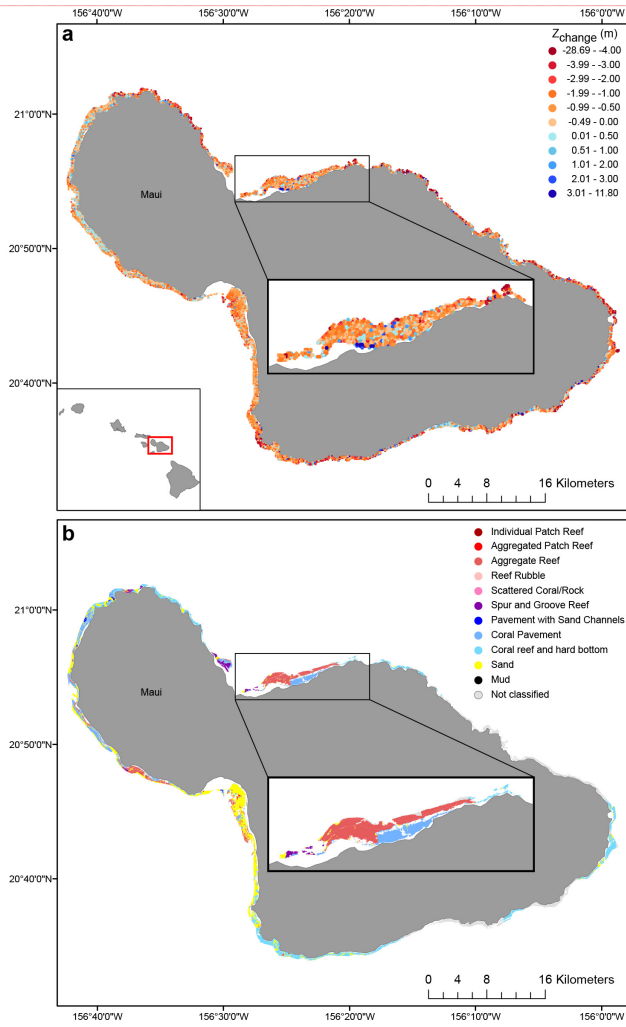


Figure 7. Elevation-change and habitat maps for Maui, Hawaii. Elevation-change over 38 years (a). Habitat (b). Elevation values are differences in meters between modern and historical elevation data ($Z_{\text{change}} = \text{modern elevation} - \text{historical}$)

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elevation, see Table S5). Inset shows magnified detail of the north central reef tract. Negative numbers indicate elevation loss, positive numbers indicate elevation gain. Habitat maps were modified from existing geo-databases (Table 3).

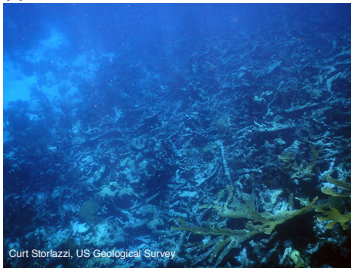
(a)



(d)



(b)



(e)



(c)



(f)



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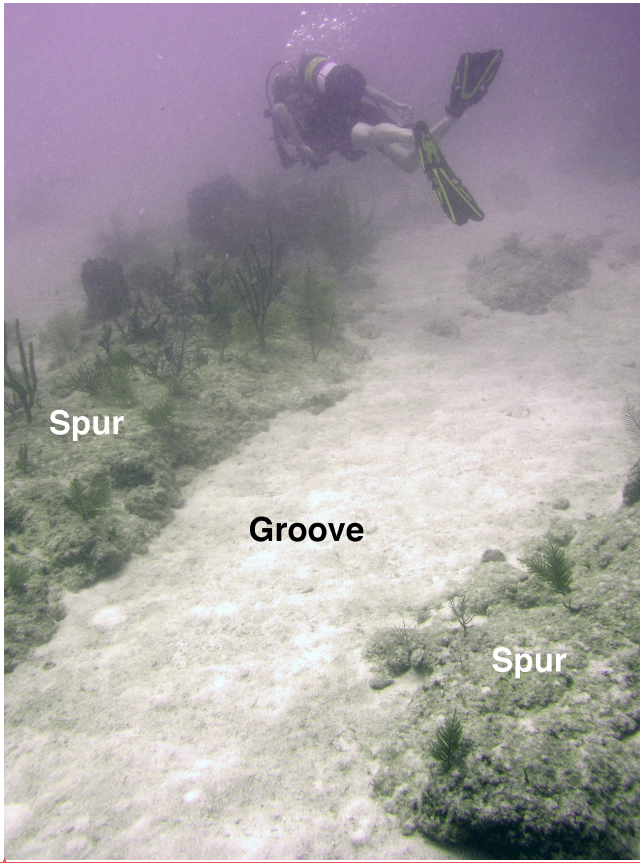
Figure 8. *Acropora palmata* coral rubble (a), (b), and (c) on the seafloor along the northeastern coast of Buck Island. Live *Acropora palmata* coral colonies (d), (e), (f) on the seafloor along the southeastern coast of Buck Island. Photo credit: C. Storlazzi, U. S. Geological Survey.

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Figure 9. Spur-and-groove formation in-filled with sediments in along the Florida Keys reef tract. Photo credit: D. Zawada, U. S. Geological Survey.

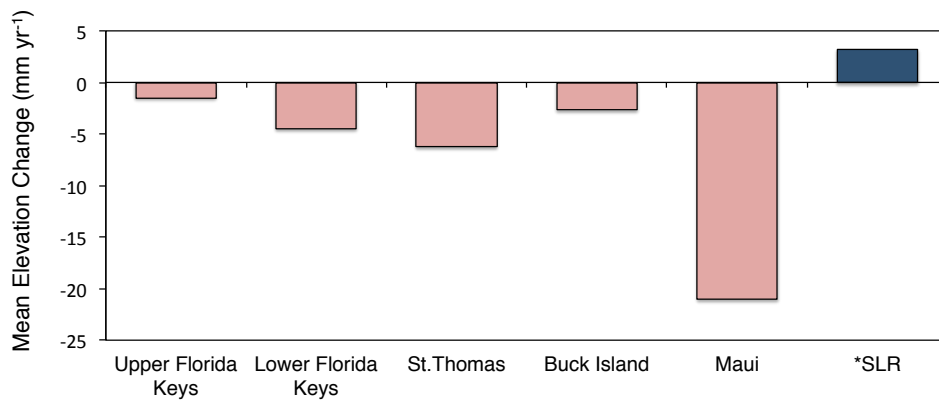


Figure 10. Mean annual elevation change calculated from total mean elevation change in meters (Table 8) divided by the time range of historical to modern bathymetric data for each study site. *SLR = global mean sea level rise of 3.2 mm yr⁻¹.

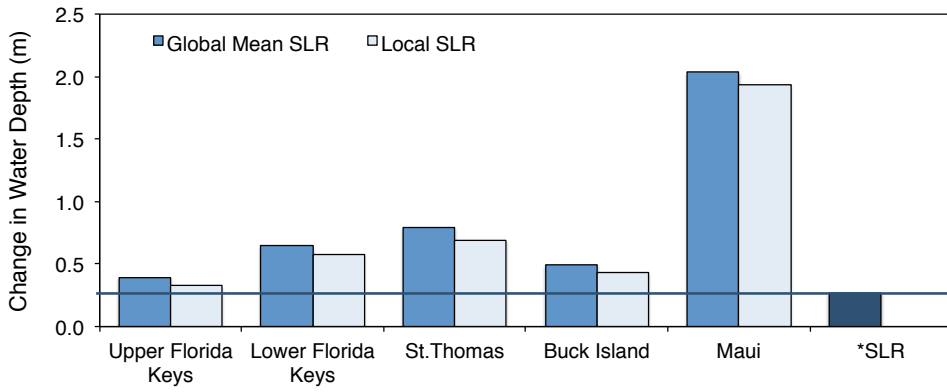
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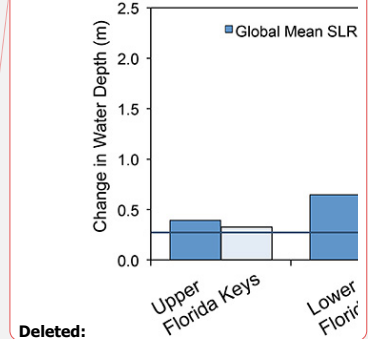
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5 **Figure 11.** Projected water depth for the year 2100. Projected change in water depth by 2100 from combined impact of mean rates of seafloor elevation loss and rising sea level based on local (a) NOAA sea-level rise trends downloaded on August 4, 2016 (<http://tidesandcurrents.noaa.gov/products.html>) and global sea level rise trends (b), see Table S6. *SLR = water depth due only to global mean sea level rise of 3.2 mm yr⁻¹

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