Building back bigger in hurricane strike zones

Eli D Lazarus[1]*, Patrick W Limber[2,3], Evan B Goldstein[4,5], Rosie Dodd[6] & Scott B Armstrong[1]

[1]Environmental Dynamics Lab, School of Geography & Environmental Science, University of Southampton, Southampton, UK

[2] Department of Marine Science, Coastal Carolina University, Conway, South Carolina, USA

[3]Pacific Coastal and Marine Science Center, United States Geological Survey, Santa Cruz, California, USA

[4]Department of Geological Sciences, University of North Carolina, Chapel Hill, North Carolina, USA

[5]Now at Department of Geography, Environment, and Sustainability, University of North Carolina at Greensboro, Greensboro, North Carolina, USA

[6]School of Earth & Ocean Sciences, Cardiff University, Cardiff, UK

*Correspondence to: E.D.Lazarus@soton.ac.uk

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[2] Department of Marine Science, Coastal Carolina University, Conway, South Carolina, USA

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[4]Department of Geological Sciences, University of North Carolina, Chapel Hill, North Carolina, USA

[5]School of Earth & Ocean Sciences, Cardiff University, Cardiff, UK

*Correspondence to: E.D.Lazarus@soton.ac.uk

ORCIDs:

ED Lazarus   0000-0003-2404-9661
PW Limber   0000-0002-8207-3750
EB Goldstein   0000-0001-9358-1016
SB Armstrong 0000-0001-9567-5964

Despite decades of regulatory efforts in the US to decrease vulnerability in developed coastal zones, exposure of residential assets to hurricane damage is increasing – even in places where hurricanes have struck before. Comparing plan-view footprints of individual residential buildings prior to and long after major hurricane strikes, we find a systematic pattern of "building back bigger" among renovated and new properties.

Storm impacts on developed coastlines are expected to increase with climate change[1]. In coastal counties around the United States, policies intended to mitigate coastal risk are competing with population growth and development pressures[1–5] that render places more vulnerable and less resilient to major storm events.

Research into the repercussions of hurricane impacts has examined regional- and local-scale socioeconomics and demographics[6–8], housing stock and types[8,9], planning and design requirements (and variances from them)[10–13], tax and insurance policy[3], and real-estate market recovery[14]. But one indicator of increasing vulnerability in hurricane zones is especially enigmatic: residential footprints are growing even in places with legacies of past impacts, including a systematic pattern of "building back bigger" among renovated and new properties.

Here, we investigate broad development trends in hurricane alleys. We measure changes over 5–14 years in residential building footprints at five locations on the US Atlantic and Gulf Coasts that have been struck by one or more hurricanes since 2003 (Fig. 1). Each location occupies a developed coastal barrier in a different state, is characterised primarily

44   by single-family residential buildings, and is demarcated in FEMA flood-risk maps a Special

45   Flood Hazard Area. Collectively, the locations have weathered six different hurricane

46   systems between 2003 and 2012, and sustained damage from multiple types of impacts

47   (e.g., wind, storm surge, waves). Each location has also had multiple years (5 or more) over

48   which residential recovery could occur. Using satellite imagery captured before the last

49   major hurricane event (or events) at each locale and again in 2017 (the most recent year of

50   coverage available at all five locations, and collected prior to the 2017 hurricane season), we

51   digitised the plan-view footprints of individual residential buildings in the pre-storm and

52   2017 imagery and compared their respective areas.

53   The resulting statistical distributions of footprint size yield the same pattern at all five

54   locations: since the last major hurricane strike, larger residential buildings have tended to

55   replace smaller ones (Fig. 2a–e). Among buildings whose footprints change (Fig. 2f–j),

56   mean footprint size increases between 19% (Hatteras) to 49% (Santa Rosa Island). Mean

57   footprints of new buildings (absent from the pre-storm image but present in 2017) exceed

58   overall pre-storm mean footprints by 14% (Mantoloking) to 55% (Santa Rosa Island).

59   Although total footprint area decreases at Mantoloking (-4%), Dauphin Island (-4%), and

60   Bolivar (-14%), the mean size of building footprints overall (insets, Fig. 2f–j) increases at all

61   five locations by 10% (Mantoloking) to 35% (Bolivar).

62   Hypothetically, total footprint area could decrease and mean footprint size increase with

63   preferential destruction or removal of small buildings, without otherwise altering the

64   footprints of existing buildings. We test for this effect by comparing the mean pre-storm

65   footprint of "surviving" buildings – those present in both images – with the mean pre-

66   storm footprint overall. The only significant difference we find is at Bolivar

67   (Supplementary Table 2), where smaller houses were disproportionately affected. However,

68   the preferential loss of smaller footprints only accounts for a 9% increase in mean

69   footprint size, which suggests the remaining ~26% increase that we calculate from 2017

70   imagery derives from renovated and new buildings. Pre-storm and 2017 distributions of

71   altered footprints (Fig. 2f–j), and of footprints overall (insets), are statistically distinct at all

72   five locations (Supplementary Table 2). Distributions of new footprints are statistically

73   distinct from overall pre-storm distributions everywhere but at Mantoloking, where only

74   nine new houses appear between 2010–2017.

75   By spanning the longest period possible since the last major hurricane event at a given

76   location, our analysis accommodates both rapid and slow paces of residential recovery.

77   Within those extended timeframes, buildings might be renovated, relocated, or removed

78   for reasons unrelated to a specific hurricane. Our method of comparing building footprints

79   does not reveal information about the cause or extent of storm damages, or about building

80   characteristics such as age, ground-floor elevation, or structural enhancements. However,

81   post-hurricane assessments have demonstrated wide variation in relationships between

82   building characteristics and hurricane damage – even among individual properties at the

83   same location subjected to the same hurricane[8,9]. The fundamental relationship from our

84   analysis is that residential footprints collectively exhibit a systemic pattern of growth in

85   hurricane zones.

86   Nationally, US houses are getting larger: between 2002–2016 (within the longest span in

87   our analysis), the mean size of new single-family houses increased 14–16% (Supplementary

88   Table 3). But the size trends that we find (Fig. 2) not only reflect greater increases

89 (Supplementary Fig. 1; Supplementary Table 3; Supplementary Methods), they also
90 manifest despite policy measures intended to prevent them. As of 2007, an estimated 16%
91 of coastal barrier land designated under the Coastal Barrier Resources Act (1982) and
92 Coastal Barrier Reauthorization Act (2000) "experienced development in spite of the
93 federal funding restrictions, encouraged by strong real estate market pressures, the
94 availability of private insurance, and state and local land-use policies that promote
95 floodplain development"[2]. Parcel-scale studies of policy effects in high-risk zones indicate
96 that even places with progressive land-use plans can have idiosyncratic development
97 patterns, typically stemming from local variances that circumvent newer planning rules[11].
98 Practices of assessment, appraisal, compliance, and enforcement hinge on local and
99 individual discretion and interpretation[10–12]. The development pattern we show across the
100 locations in Fig. 1 surely arose from a number of mechanisms[3,5,7–14]. However, the aggregate
101 effect of those mechanisms – including the tendency to "build back bigger" in hurricane
102 corridors and demarcated coastal flood-risk zones – appears insensitive to their particulars.

103 By demonstrating an emergent pattern of increased exposure in high-risk coastal
104 development, we intend for our analysis to complement local case studies of land-use
105 policy effects and hazard-mitigation strategies. Related "build-destroy-rebuild"
106 patterns[10,15,16] appear in a variety of other hazard settings[17,18], with critical implications for
107 future management and policy actions[2,19]. Comparative research across different hazard
108 types (e.g., earthquakes, wildfires, tornadoes)[17–19] and longitudinal studies quantifying
109 changes to built environments[7] in vulnerable areas (not limited to the US[20]) will help the
110 wider sustainability-science research community to identify, understand, address the
111 economic and policy forces that shape decision-making and risk evolution in places where
112 climate-related hazards are intensifying.

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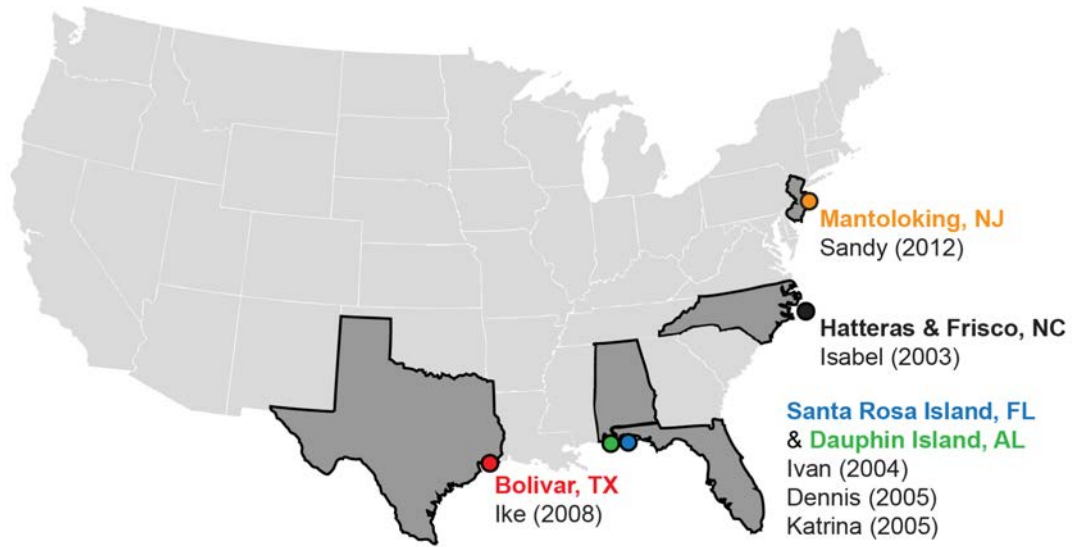142   doi:10.6084/m9.figshare.7105835 (2018).

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150   **Author contributions**

151   PWL conceived of the idea; all authors contributed to data collection; EDL, PWL, EBG,
152   and RD conducted the analysis; EDL, EBG, and PWL wrote the manuscript, with
153   contributions from RD and SBA.

154   **Figure Legends**

155

156   **Figure 1 |** Study locations in hurricane strike zones around the US Atlantic and Gulf
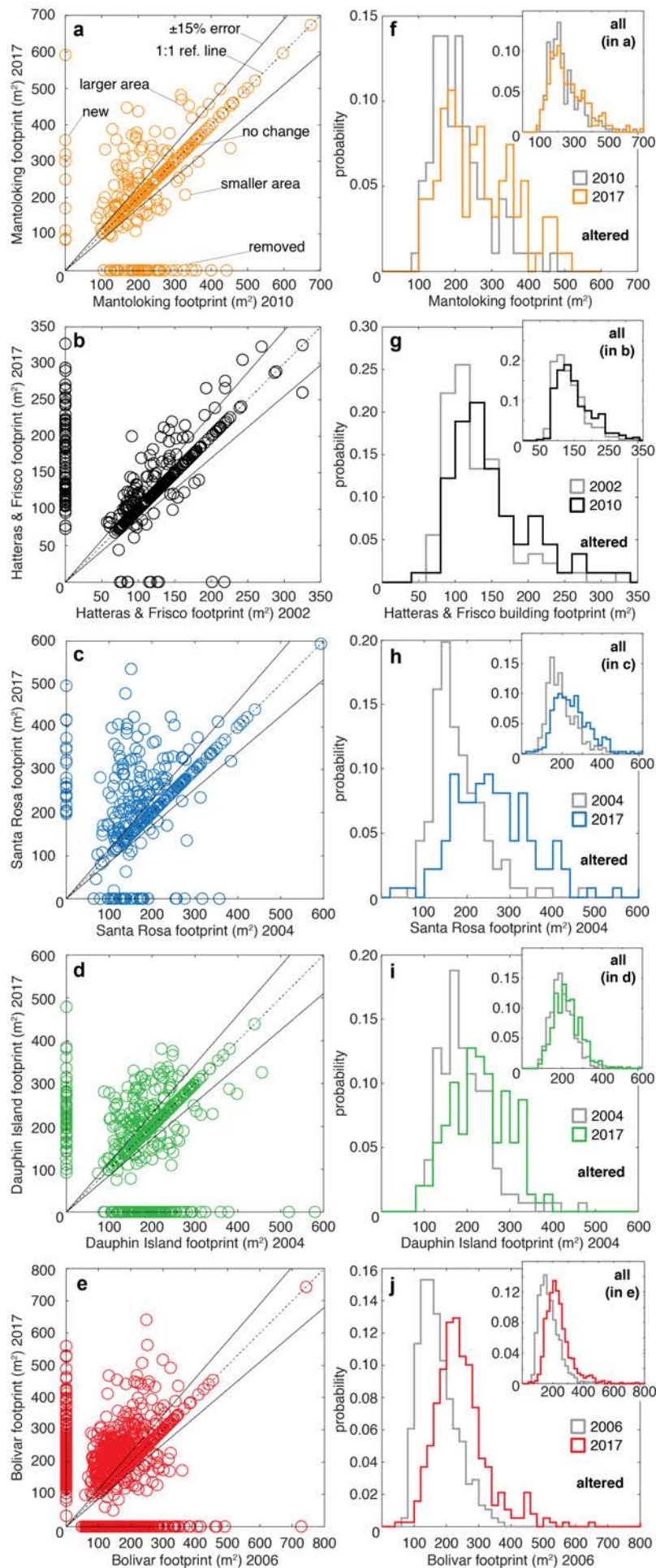157   Coasts.

158
159

Figure 2 | Evidence of "building back bigger" in hurricane strike zones. **a–e,** Comparisons of building footprint size in pre-storm versus 2017 images, showing categorical changes in residential development. Footprints for which the 2017 area is ±15% (solid lines) of the pre-storm area are considered unchanged (assumes difference is indistinguishable from potential error). Dotted line marks reference line of 1:1 correspondence. **f–j,** Pre-storm and 2017 distributions of building footprints that changed in area; insets show pre-storm and 2017 distributions of all footprints. Note scales of axes differ by location. (Descriptive statistics and comparative tests for the data in this figure are available in Supplementary Tables 1 and 2.)

Methods

Building footprints – We use publicly available imagery of requisite resolution and an appropriate capture date, spanning a full timeframe from prior to the last major hurricane strike at each location up to the most recent available imagery (2017). Pre-storm and 2017 imagery for Mantoloking, Santa Rosa Island, Dauphin Island, and the Bolivar peninsula is sourced from Google Earth. Pre-storm imagery (2002) for Hatteras Village and Frisco (combined as "Hatteras") comes from the NC OneMap GeoSpatial Portal (http://data.nconemap.gov/geoportal/catalog/raster/download.page). FEMA Flood Risk Zone designations are available through the agency's Map Service Center (https://msc.fema.gov/portal/).

Building footprints were digitised manually and their areas calculated using GIS software. We digitised the roofed footprint of every residential building in the first three rows back from the "ocean-side" shorefront. At Mantoloking, north/south town boundaries set the sampling space. At Santa Rosa Island, we sampled the reach of coastline between the causeways at Pensacola Beach and Navarre Beach (west/east, respectively). At Hatteras/Frisco, Dauphin Island, and the Bolivar Peninsula (immediately northeast of Galveston), we sampled the full alongshore extents. These data (pre-storm and 2017 combined, ~4800 footprints) therefore represent a large sample or all of the single-family residential buildings at each location. Footprints were matched between images using a spatial join, then reviewed manually. Given inherent variability in pre-storm image quality (resolution or image tilt), we use a compensatory envelope of ±15%, which assumes that a building's 2017 footprint must change more than ±15% to be distinguishable from potential error. This envelope is nearly four to five times greater than the ~3–4% error variance attributable to our manual digitisation, and is therefore a conservative measure.

Summary magnitudes of change in footprint area do not correlate with elapsed time between images, nor do they indicate a geographic control (i.e., Atlantic versus Gulf Coast). Although we did not control for building characteristics (or demographics), we applied the same method to five distinct locations (each with ~10–30 km of shoreline extent) and found the same pattern everywhere, suggesting that contextual biases in any one sample are not strong enough to skew the aggregate findings.

In the Supplementary Methods, we further discuss our locations, and compare a subset of our measured footprints to total living area reported in tax records (Supplementary Fig. 1; Supplementary Table 3).

Statistical analysis – To quantitatively distinguish between pre-storm and 2017 distributions of building size (Fig. 2f–j and insets), we used a two-sample Kolmogorov-Smirnov (K-S) test with the null hypothesis that the two distributions could have come from the same continuous distribution. (A K-S test is applicable to non-parametric data.) We tested to the $\alpha = 5\%$ significance level (two-tailed); the asymptotic value p is the probability of observing an equal or greater test statistic. Because some of the distributions are only weakly non-parametric, we also applied a paired *t*-test (for normal distributions), and find the same results. Sample sizes (n) and values for significant and non-significant K-S and paired-*t* tests are shown in Supplementary Table 2.

Data availability – Study data are available via Figshare (Lazarus, E. D., Limber, P. W. & Goldstein, E. B. Data for "Building back bigger in hurricane strike zones", *Figshare* doi:10.6084/m9.figshare.7108763 (2018) [Ref. 21]). Coordinates for the start- and endpoints of the sampled areas are shown in Supplementary Table 4.

SUPPLEMENTARY INFORMATION

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[1]Environmental Dynamics Lab, School of Geography & Environmental Science, University of Southampton, Southampton, UK

[2] Department of Marine Science, Coastal Carolina University, Conway, South Carolina, USA

[3]Pacific Coastal and Marine Science Center, United States Geological Survey, Santa Cruz, California, USA

[4]Department of Geological Sciences, University of North Carolina, Chapel Hill, North Carolina, USA

[5]School of Earth & Ocean Sciences, Cardiff University, Cardiff, UK

*Correspondence to: E.D.Lazarus@soton.ac.uk

SUPPLEMENTARY METHODS

Locations – We examined five locations on the US Atlantic and Gulf Coasts that have been struck by one or more hurricanes since 2003. Our selection of locations was determined in part by date and image suitability: satellite imagery collected prior to 2002 tended to lack resolution crisp enough for reliable digitisation. Collectively, these five locations have weathered six different hurricane systems between 2003 and 2012, and sustained damage from multiple types of impacts (e.g., wind, storm surge, waves). Each location occupies a developed coastal barrier in a different state, and, although FEMA flood-risk maps are known to vary in their quality and accuracy (see Supplementary Ref. 1), each location is demarcated in FEMA flood-risk maps a Special Flood Hazard Area – either Zone A (hundred-year flood zones) or Zone V (hundred-year coastal flood zones likely to experience "velocity" from storm surge or wave action). These traits thus lend the locations similar physical environmental settings and federal designations, but potentially different state and local land-use planning contexts. Furthermore, by spanning the longest period possible (5 years or longer) since the last major hurricane event at a given location, our analysis allows for both rapid and slow paces of residential recovery. (That is, aerial images from the 2017 hurricane season, for example, might show damage but not reconstruction.)

Each location is characterised primarily by single-family residential buildings: where possible, we confirmed this building-type classification with tax records (Supplementary Fig. 1). To sample conservatively, we did not digitise buildings with visible adjacent parking lots, assuming they served either multi-unit condominiums or commercial buildings. Although a given building may have changed from a single-family residence to a commercial space (or vice versa), we expect the impact of any such buildings on the statistical analysis is negligible, given the large number of individual buildings we sampled.

This analysis is preliminary: it is limited to five US sites, and is not an exhaustive list of all sites on developed coastal barriers that have sustained hurricane damage (even in the US). Nevertheless, these preliminary results are instructive and motivate further work. Depending on imagery and data availability, the same comparative-footprint approach could be extended to other locations prone to cyclones (or other hazard types), and even applied in the absence of any recent cyclone (or other hazard) activity. Integrating a deliberately simplified analysis like ours with detailed collation of tax records, permits, construction types, and code variances (see Refs. 8, 11 & 12 in the main text) would reflect the influence of political, legal, planning and other policy mechanisms in the coastal zone. But even in the absence of such detailed homeowner data (particularly outside the US), our methodology still quantifies broad development trends in ways that may help the wider sustainability-science research community to identify, understand, address the economic and policy forces that shape decision-making and risk evolution in hurricane alleys (and other hazard zones).

Comparison of total living area to measured footprints – Property taxes (and national Census statistics) report the total living area of a house, not its plan-view footprint. The roofed footprint that we digitise might approximately match the total living area for a single-storey house, but will almost certainly under-predict the total living area of a multi-storey building. For a building with deep covered porches, which do not count toward living area, our measurement of the roofed footprint will tend to over-predict the size of the actual (taxed) total living area.

To estimate how our footprint data scale relative to total living area, we compared the 2017 footprints of front-row properties from Hatteras/Frisco and Santa Rosa Island to total living area reported in property tax records as of 2016 (Supplementary Fig. 1). We use these two locations because their tax records are publicly available online: Hatteras/Frisco via Dare County (https://tax.darecountync.gov/parcelcard.php?parcel=); Santa Rosa Island

via the Florida Geographic Data Library
(https://www.fgdl.org/metadataexplorer/explorer.jsp).

We find that total living area is, on average, ~94% larger than footprint area at Hatteras/Frisco, and ~39% higher at Santa Rosa Island (Supplementary Fig. 1, insets). Applying these scaling factors, respectively, to our mean footprints allows us to compare our measurements to national statistics (via the US Census Bureau) for mean total floor area in new single-family houses (Supplementary Table 3). By direct comparison, according to the sizes reported in tax records, the mean size of (front-row) single-family residential buildings in our 2017 sample from Hatteras/Frisco are 28% larger than the 2016 national average for new single-family houses; our sample from Santa Rosa Island are 47% larger than the 2016 national average.

Note that our measured samples include all existing buildings, not just those built most recently. Hypothetically, a location where development exactly matches the national trend in new houses each year will, over time, end up with an overall mean house size that is smaller than the mean size for the most recent year. (For example: the mean of the national mean new house size between 2002–2016 is 231 m^2, or 6% smaller than the national mean for new houses (245 m^2) in 2016.)

Supplementary References

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SUPPLEMENTARY FIGURES
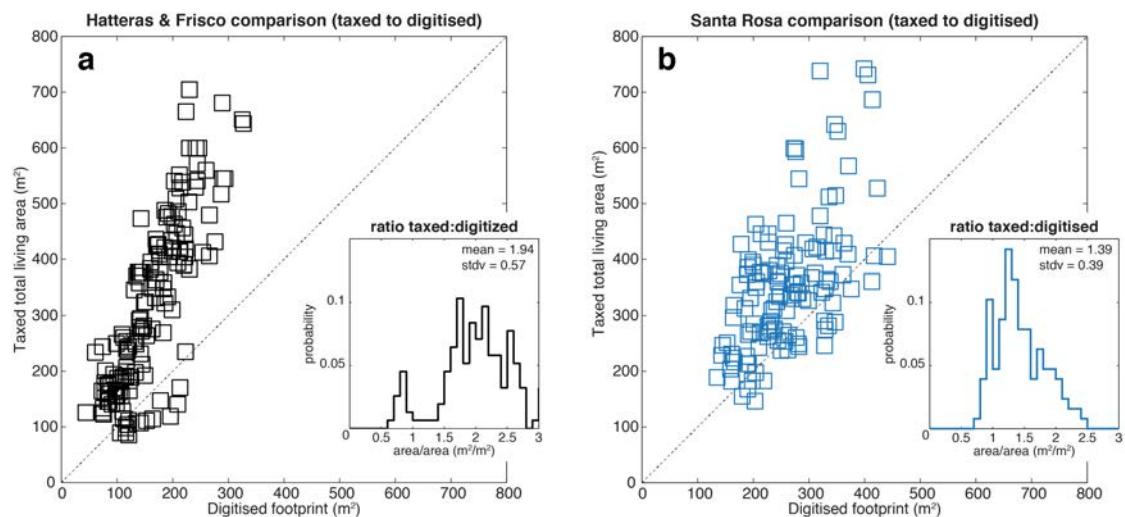
Supplementary Figure 1 | Comparison of taxed total living area to footprint area. **a,** Scaling relationship for Hatteras/Frisco, with ratio distribution (taxed to digitised) shown in inset. **b,** Scaling relationship for Santa Rosa Island. These data reflect shorefront (first row), single-family houses from both locations, and compare 2016 tax information to footprints digitised from 2017 imagery (data presented in the main article). Dotted lines show the 1:1 reference line.

SUPPLEMENTARY TABLES

Supplementary Table 1 | Descriptive statistics for footprint data (sample counts, totals, means) in this study. (For comparative statistical tests, see Supplementary Table 2.)

	Mantoloking	Hatteras	Santa Rosa	Dauphin	Bolivar	
Imagery						
pre-storm year[a]	2010	2002	2004	2004	2006	
"final" year[b]	2017	2017	2017	2017	2017	
years between images	7	15	13	13	11	
storm year(s)	2012	2003	2004, 2005	2004, 2005	2008	
years since last hurricane strike	5	14	12	12	7	
Numbers in sample						*totals*
pre-storm image (all)	287	304	306	462	1295	*2654*
2017 image (all)	252	375	291	401	823	*2142*
total altered	94	90	136	149	379	*848*
altered+ (area increased)	67	74	121	112	339	*713*
altered- (area decreased)	27	16	15	37	40	*135*
new build	9	81	20	60	196	*366*
removed	44	10	35	121	668	*878*
altered as % pre-storm total	33%	30%	44%	32%	29%	
altered+ as % altered	71%	82%	89%	75%	89%	
altered- as % altered	29%	18%	11%	25%	11%	
new as % 2017 total	4%	22%	7%	15%	24%	
removed as % pre-storm total	15%	3%	11%	26%	52%	
Total footprint areas (m²)						
pre-storm (all)	67343	38350	57493	90375	217767	
2017 (all)	64979	53713	70088	87030	186596	
altered (pre-storm area)	19253	10787	22951	27300	61988	
altered (2017 area)	23919	12794	34222	33099	89590	
altered+ (pre-storm area)	12961	8552	19927	18689	52770	
altered+ (2017 area)	19220	11084	32046	26989	83450	
new	2271	14136	5902	13979	44184	
removed	9539	1228	5537	23192	103684	
difference 2017 to pre (all)	-2364	15363	12595	-3345	-31171	
difference as % pre (all)	-4%	40%	22%	-4%	-14%	
difference 2017 to pre (altered)	4666	2007	11271	5799	27602	
difference as % pre (altered)	24%	19%	49%	21%	45%	
new as % post (all)	3%	26%	8%	16%	24%	
removed as % pre (all)	14%	3%	10%	26%	48%	
Footprint (m²) means: all (1 stdv)						
pre-storm	235 (118)	126 (46)	188 (73)	196 (65)	168 (69)	
2017	258 (134)	143 (53)	241 (90)	217 (64)	227 (84)	
difference	23	17	53	21	59	
difference as % pre	10%	14%	28%	11%	35%	
Footprint (m²) means: altered (1 stdv)						
pre-storm	205 (77)	120 (47)	169 (62)	183 (60)	164 (58)	
2017	254 (101)	142 (56)	252 (95)	222 (68)	236 (87)	
difference	50	22	83	39	72	
difference as % pre	24%	19%	49%	21%	44%	
altered+ pre (mean)	193 (74)	116 (44)	165 (58)	167 (44)	185 (66)	
altered+ 2017 (mean)	287 (96)	150 (55)	265 (89)	241 (60)	291 (105)	
diff. in altered+ (2017 to pre)	93	34	100	74	105	
diff. in altered+ as % pre altered+	48%	30%	61%	44%	57%	
altered- pre (mean)	233 (80)	140 (59)	202 (84)	233 (76)	258 (71)	
altered- 2017 (mean)	174 (63)	107 (49)	145 (77)	165 (57)	176 (54)	
diff. in altered- (2017 to pre)	-59	-33	-57	-68	-82	
diff. in altered- as % pre altered-	-25%	-23%	-28%	-29%	-32%	
Footprint (m²) means: new (1 stdv)						
pre-storm ('pre-storm means all', above)	235 (118)	126 (46)	188 (73)	196 (65)	168 (69)	
2017	252 (164)	175 (56)	295 (83)	233 (71)	225 (90)	
difference	18	48	107	37	57	
difference as % pre	14%	26%	55%	19%	34%	

[a] Imagery from 2004 (for Santa Rosa Island and Dauphin Island) was captured in March; Hurricane Ivan passed in September.

[b] Imagery from 2017 for Bolivar was captured in February, several months prior to the 2017 hurricane season.

Supplementary Table 2 | Statistical tests (Kolmogorov-Smirnov; two-sample t test) comparing pre-storm and 2017 footprint distributions (shown in Fig. 2) and comparing pre-storm versus "survivor" footprints. All tests are two-tailed at $\alpha = 5\%$ significance level; all areas in m². (Table footnotes on next page.)

	Mantoloking	Hatteras	Santa Rosa	Dauphin	Bolivar
Comparison of <u>all</u> building footprints (pre-storm to 2017)					
Distribution statistics: all footprints (m²)					
number in sample: pre-storm image	287	304	306	462	1295
number in sample: 2017 image	252	375	291	401	823
pre-storm mean footprint area (1 stdv)	235 (118)	126 (46)	188 (73)	196 (65)	168 (69)
2017 mean footprint area (1 stdv)	258 (134)	143 (53)	241 (90)	217 (64)	227 (84)
difference	23	17	53	21	59
difference as % pre-storm	10%	14%	28%	11%	35%
KS test: all footprints (sample size *n*; pre-storm & 2017) – null hypothesis: samples come from same distribution					
hypothesis (1 = reject null) [a]	1 (287, 252)	1 (304, 375)	1 (306, 291)	1 (462, 401)	1 (1295, 823)
p-value[b]	4.31E-02	5.05E-04	1.96E-13	1.26E-08	8.68E-55
test statistic	0.1183	0.1555	0.3136	0.2079	0.3507
paired *t* test: all footprints (sample size *n*; pre-storm & 2017) – null hypothesis: samples come from same distribution					
hypothesis (1 = reject null) [c]	1 (287, 252)	1 (304, 375)	1 (306, 291)	1 (462, 401)	1 (1295, 823)
p-value	0.0329	1.05E-05	1.37E-14	1.49E-6	3.72E-64
Comparison of <u>altered</u> building footprints (pre-storm to 2017)					
Distribution statistics: altered footprints (m²)					
number in sample: altered	94	90	136	149	379
pre-storm mean footprint area (1 stdv)	205 (77)	120 (47)	169 (62)	183 (60)	164 (58)
2017 mean altered footprint area (1 stdv)	254 (101)	142 (56)	252 (95)	222 (68)	236 (87)
difference	50	22	83	39	72
difference as % pre-storm	24%	19%	49%	21%	44%
KS test: altered footprints (sample size *n*; pre-storm & 2017) – null hypothesis: samples come from same distribution					
hypothesis (1 = reject null)	1 (94, 94)	1 (90, 90)	1 (136,136)	1 (149, 149)	1 (379, 379)
p-value	2.00E-03	1.40E-03	1.63E-13	4.60E-07	9.12E-34
test statistic	0.2660	0.2778	0.4632	0.3154	0.4459
paired *t* test: altered footprints (sample size *n*; pre-storm & 2017) – null hypothesis: samples come from same distribution					
hypothesis (1 = reject null)	1 (94, 94)	1 (90, 90)	1 (136,136)	1 (149, 149)	1 (379, 379)
p-value	2.13E-04	0.0044	1.34E-15	2.99E-07	8.82E-38
Comparison of <u>new</u> building footprints (pre-storm to 2017)					
Distribution statistics: new footprints (m²)					
number in sample: pre-storm image	287	304	306	462	1295
number in sample: new since pre-storm	9	81	20	60	196
pre-storm mean footprint area (1 stdv)	235 (118)	126 (46)	188 (73)	196 (65)	168 (69)
2017 mean new footprint area (1 stdv)	252 (164)	175 (56)	295 (83)	233 (71)	225 (90)
difference	18	48	107	37	57
difference as % pre-storm	14%	26%	55%	19%	34%
KS test: new footprints (sample sizes *n*; pre-storm all & new) – null hypothesis: samples come from same distribution					
hypothesis (1 = reject null)	0 (287, 9)	1 (304, 81)	1 (306, 20)	1 (462, 60)	1 (1295, 196)
p-value	0.3405	2.15E-09	8.59E-08	5.10E-07	7.53E-14
test statistic	0.3020	0.3952	0.6503	0.3712	0.2984
paired *t* test: new footprints (sample sizes *n*; pre-storm all & new) – null hypothesis: samples come from same distribution					
hypothesis (1 = reject null)	0 (287, 9)	1 (304, 81)	1 (306, 20)	1 (462, 60)	1 (1295, 196)
p-value	0.3405	2.15E-09	8.59E-08	5.10E-07	7.73E-14
Comparison of "surviving" building footprints[d] (pre-storm to 2017)					
Distribution statistics: surviving building footprints (m²)					
number in sample: pre-storm image (all)	287	304	306	462	1295
number in sample: surviving buildings	243	293	270	341	627
surviving buildings as % of pre-storm total	85%	96%	88%	74%	48%
pre-storm mean footprint area all (1 stdv)	235 (118)	126 (46)	188 (73)	196 (65)	168 (69)
"surviving" mean footprint area (1 stdv)	239 (129)	128 (46)	195 (77)	197 (61)	183 (67)
difference as % of "pre-storm all" mean	2%	2%	4%	1%	9%
KS test: surviving buildings (sample size *n*; pre-storm all & surviving) – null hypothesis: samples come from same distribution					
hypothesis (1 = reject null)	0 (287, 243)	0 (304, 293)	0 (306, 270)	0 (462, 341)	1 (1295, 627)
p-value	0.9998	0.9992	0.4159	0.60889	1.72E-05
test statistic	0.0296	0.02996	0.0730	0.0538	0.1168
paired *t* test: surviving buildings (sample size *n*; pre-storm all & surviving) – null hypothesis: samples come from same distribution					
hypothesis (1 = reject null)	0 (287, 243)	0 (304, 293)	0 (306, 270)	0 (462, 341)	1 (1295, 627)
p-value	0.6956	0.9992	0.2262	0.7223	7.82E-06

Supplementary Table 3 | Comparisons of data from this study to national trends in house size.

	Mantoloking	Hatteras	Santa Rosa	Dauphin	Bolivar
National mean total floor area (m^2) in new single-family houses completed[a]					
image pairs (pre-storm year, 2017)	2010, 2017	2002, 2017	2004, 2017	2004, 2017	2006, 2017
mean area in year of pre-storm image	222	216	218	218	229
mean area in "final" year (2016)[b]	245	245	245	245	245
difference (post to pre)	23	29	27	27	16
change as % pre-storm mean	10%	14%	12%	12%	7%
max. area in pre/post span (year)	250 (2015)	250 (2015)	250 (2015)	250 (2015)	250 (2015)
max. difference[c]	28	34	32	32	21
max. change as % pre-storm mean	12%	16%	14%	14%	9%
Footprints (this study)					
change as % pre-storm mean (all)	10%	14%	28%	11%	35%
change as % pre-storm mean (altered)	24%	19%	49%	21%	44%
change as % pre-storm mean (new)	14%	26%	55%	19%	34%
Footprints – total living area (taxed) vs digitised footprint					
sample size (n, from front row only)	-	156	128	-	-
mean taxed total living area (m^2, 1 stdv)	-	313 (155)	360 (133)	-	-
mean ratio (taxed area to post footprint)	-	1.94	1.39	-	-
standard deviation of mean ratio	-	0.57	0.39	-	-
% diff. relative to 2016 national mean	-	28%	47%	-	-
Footprint means: scaled estimations (see Supplementary Fig. 1 & Supplementary Methods)[d]					
mean footprints (pre, all) x 1.4	329	176	**263**	274	235
as % national mean (pre)	48%	-18%	**21%**	26%	3%
mean footprints (2017, all) x 1.4	361	200	**337**	304	318
as % national mean (2017)	47%	-18%	**38%**	24%	30%
mean footprints (pre, altered) x 1.4	287	168	**237**	256	230
as % national mean (pre)	29%	-22%	**9%**	18%	≈
mean footprints (2017, altered) x 1.4	356	199	**353**	311	330
as % national mean (2017)	45%	-19%	**44%**	27%	35%
mean footprints (new) x 1.4	353	245	**413**	326	315
as % national mean (2017)	44%	0%	**69%**	33%	29%
mean footprints (pre, all) x 1.9	447	**239**	357	372	319
as % national mean (pre)	101%	**11%**	64%	71%	39%
mean footprints (2017, all) x 1.9	490	**272**	458	412	431
as % national mean (2017)	100%	**11%**	87%	68%	76%
mean footprints (pre, altered) x 1.9	390	**228**	321	348	312
as % national mean (pre)	75%	**6%**	47%	59%	36%
mean footprints (2017, altered) x 1.9	483	**270**	479	422	448
as % national mean (2017)	97%	**10%**	95%	72%	83%
mean footprints (new) x 1.9	479	**333**	561	443	428
as % national mean (2017)	95%	**36%**	129%	81%	74%

Supplementary Table 4 | End-point coordinates (in decimal degrees) for locations sampled (see also Ref. 21 in main article for data repository).

Location	Start (north or west)	End (south or east)
Mantoloking, NJ	40.058447°, -74.045709°	40.026381°, -74.053804°
Hatteras/Frisco, NC	35.205950°, -75.702756°	35.229029°, -75.625388°
Santa Rosa, FL	30.333611°, -87.130948°	30.378038°, -86.880504°
Dauphin, AL [segment 1]	30.248554°, -88.191982°	30.251080°, -88.138527°
Dauphin, AL [segment 2]	30.244266°, -88.105405°	30.247469°, -88.076565°
Bolivar, TX	29.396736°, -94.718203°	29.521562°, -94.462669°