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Building back bigger in hurricane strike zones

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1 Building back bigger in hurricane strike zones

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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 planview 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.

- 29 Storm impacts on developed coastlines are expected to increase with climate change¹. In
- 30 coastal counties around the United States, policies intended to mitigate coastal risk are
- 31 competing with population growth and development pressures^{1–5} that render places more
- 32 vulnerable and less resilient to major storm events.
- 33 Research into the repercussions of hurricane impacts has examined regional- and local-
- 34 scale socioeconomics and demographics^{6–8}, housing stock and types^{8,9}, planning and design
- 35 requirements (and variances from them)^{10–13}, tax and insurance policy³, and real-estate
- 36 market recovery¹⁴. But one indicator of increasing vulnerability in hurricane zones is
- 37 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 newproperties.
- 40 Here, we investigate broad development trends in hurricane alleys. We measure changes
- 41 over 5–14 years in residential building footprints at five locations on the US Atlantic and
- 42 Gulf Coasts that have been struck by one or more hurricanes since 2003 (Fig. 1). Each
- 43 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 $\sim 26\%$ 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
- that even places with progressive land-use plans can have idiosyncratic development
- 97 patterns, typically stemming from local variances that circumvent newer planning rules¹¹.
- 98 Practices of assessment, appraisal, compliance, and enforcement hinge on local and
- 99 individual discretion and interpretation¹⁰⁻¹². 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 environments⁷ in vulnerable areas (not limited to the US²⁰) 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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150 Author contributions

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

Figure Legends 154



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

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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 $\pm 15\%$ (solid lines) of the prestorm area are considered unchanged (assumes difference is indistinguishable from potential error). Dotted line marks reference line of 1:1 correspondence. f-i, 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.)

198 Methods

- 199 Building footprints We use publicly available imagery of requisite resolution and an
- 200 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
- 202 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
- 204 (combined as "Hatteras") comes from the NC OneMap GeoSpatial Portal
- 205 (http://data.nconemap.gov/geoportal/catalog/raster/download.page). FEMA Flood Risk
- 206 Zone designations are available through the agency's Map Service Center
- 207 (https://msc.fema.gov/portal/).
- 208 Building footprints were digitised manually and their areas calculated using GIS software.
- 209 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
- 212 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)
- 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
- 217 residential buildings at each location. Footprints were matched between images using a 217 spatial join, then reviewed manually. Given inherent variability in pre-storm image quality
- 217 spatial join, then reviewed manually. Given interent variability in pre-storm image quality 218 (resolution or image tilt), we use a compensatory envelope of $\pm 15\%$, which assumes that a
- building's 2017 footprint must change more than $\pm 15\%$ to be distinguishable from
- potential error. This envelope is nearly four to five times greater than the $\sim 3-4\%$ error
- 221 variance attributable to our manual digitisation, and is therefore a conservative measure.
- 222 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).
- 224 Although we did not control for building characteristics (or demographics), we applied the
- same method to five distinct locations (each with $\sim 10-30$ 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).
- 231 Statistical analysis To quantitatively distinguish between pre-storm and 2017 distributions
- 232 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
- 234 continuous distribution. (A K-S test is applicable to non-parametric data.) We tested to the
- 235 $\alpha = 5\%$ significance level (two-tailed); the asymptotic value *p* is the probability of
- 236 observing an equal or greater test statistic. Because some of the distributions are only
- 237 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
- 239 paired-*t* tests are shown in Supplementary Table 2.
- 240 Data availability Study data are available via Figshare (Lazarus, E. D., Limber, P. W. &
- 241 Goldstein, E. B. Data for "Building back bigger in hurricane strike zones", Figshare
- 242 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

Building back bigger in hurricane strike zones

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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 m², or 6% smaller than the national mean for new houses (245 m²) 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	
•	Ű		.2		•	
Numbers in sample						totals
pre-storm image (all)	287	304	306	462	1295	265
2017 image (all)	252	375	291	401	823	214
total altered	94	90	136	149	379	84
altered+ (area increased)	67	74	121	112	339	71
altered- (area decreased)	27	16	15	37	40	13
new build	9	81	20	60	196	36
removed	44	10	35	121	668	87
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%	
	1070	070	1170	2070	0270	
Total footprint areas (m ²)	67343	38350	57493	90375	217767	
pre-storm (all)	64979	38350 53713	70088			
2017 (all)				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 (m ²) 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	230 (104)	140 (00)	53	217 (04)	59	
difference as % pre	10%	14%	28%	11%	35%	
•	1070	1470	2070	1170	0070	
Footprint (m ²) means: altered (1 stdv) pre-storm	205 (77)	120 (47)	160 (62)	192 (60)	164 (59)	
2017	205 (77)	120 (47)	169 (62)	183 (60)	164 (58)	
	254 (101)	142 (56)	252 (95)	222 (68)	236 (87)	
difference	50	22 19%	83 49%	39	72 44%	
difference as % pre	24%			21%		
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.)

Comparison of all building footprints (pro- tumber in sample: 2017 image) 262 304 306 4021 1225 number in sample: 2017 image 2262 306 4021 4021 4011 682 2017 image 2262 304 4011 227 4011 2017 image 2217 4011 2217 2217 401 2017 image 2217 10304 2117 633 2117 635 2017 10304, 370 114054 14202 50504 10424 01305 2027 03357 pravale ¹ 1287.70 1199054 1199054 1199054 1199054 1199054 1199054 1199054		Mantoloking	Hatteras	Santa Rosa	Dauphin	Bolivar
number in sample: pre-storm image 287 394 306 402 1935 number in sample: pre-storm image 282 375 281 401 1883 (0) 2017 mana hodprint area (1 stor) 226 (118) 126 (46) 188 (7) 196 (65) 116 (66) 2017 mana hodprint area (1 stor) 223 177 63 271 315 2017 mana hodprint area (1 stor) 11287, 252 1 (304, 375) 1 (306, 201) 1 (426, 201) 1 (206, 821) pre-ataler 4 (316 c2 5.054 c4 1.986-13 1.286-8 8.86 c5 test static 0 (118) 0 (155 0 (316) 0 (207) 0 .0307 parader 0 (232 1 (306, 375) 1 (306, 201) 1 (426, 401) 1 (296, 228) parader 0 (232 1 (306, 375) 1 (306, 201) 1 (426, 401) 1 (296, 228) pre-ataler 0 (232 1 (306, 375) 1 (306, 376) 1 (406, 326) 2017 mana atteriot dopint as (1 stor) 205 (77) 1 20 (47) 1 60 (25) 1 83 (60) 1 40 (45) <t< th=""><th>Comparison of all building footprint</th><th>s (pre-storm to 20</th><th>17)</th><th></th><th></th><th></th></t<>	Comparison of all building footprint	s (pre-storm to 20	17)			
number in sample: 2017 mage 252 375 291 401 682 per-storm mean footprint area (14bh) 228 (114) 142 (46) 118 (73) 196 (65) 110 (66) 2017 mean footprint area (14bh) 228 (124) 144 (53) 241 (90) 217 (94) difference as % pre-storm 10% 14% 28% 11% 38% KS test: all footprints (sample size r, pre-storm & 2017) - null hypothesis: samples come from same distribution 1(282, 282) 1(204, 37) 1(208, 21) 1(462, 201) 1(1285, 823) p-value 0.138 0.1565 0.3360 0.2079 0.3607 p-value 0.0220 1.066-05 1.37E-14 1.49E, 401 1(1285, 823) p-value 0.0220 1.06E-05 1.37E-14 1.49E, 401 1.1285, 823 p-value 0.0220 1.06E-05 1.37E-14 1.49E, 401 1.028, 823 p-value 0.226 (77) 120 (47) 109 (42) 136 (00) 101 (462, 90) 2017 mean altered biolprint area (1369) 224 (101) 142 (50) 221 (263, 37) p	Distribution statistics: all footprints (m ²)					
pre-storm mean fourpoint area (1 staby) 228 (116) 128 (40) 148 (15) 24 (160) 127 (166) 227 (164) difference as pre-storm 23 17 5.5 211 (165) 228 111% 3355 difference as pre-storm 210 1 (257, 252) 1 (204, 375) 1 (206, 201) 1 (462, 401) 1 (1255, 822) pravale 4 (312, 252) 1 (204, 375) 1 (206, 201) 1 (462, 401) 1 (1255, 822) pravale 4 (312, 252) 1 (304, 375) 1 (306, 201) 1 (462, 401) 1 (1255, 822) pravale 0 (322) 1 (304, 375) 1 (306, 201) 1 (462, 401) 1 (1255, 822) pravale 0 (322) 1 (304, 375) 1 (306, 201) 1 (462, 401) 1 (1255, 822) pravale 0 (322) 1 (304, 375) 1 (306, 201) 1 (462, 401) 1 (1255, 822) pravale 0 (287) 1 (304, 375) 1 (306, 201) 1 (462, 401) 1 (1255, 822) pravale 0 (287) 1 (287, 379) 1 (306, 201) 1 (462, 401) 1 (275, 379) pre	number in sample: pre-storm image	287	304	306	462	1295
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difference 23 177 33 211 93 difference as % pre-storm 101% 114% 22% 111% 35% KS test: all footprints (sample size r; pre-storm & 2017) – null hypothesis: samples come from same distribution 11(205, 82) 12(87, 82) 12(82, 62) 12(82	pre-storm mean footprint area (1 stdv)	235 (118)	126 (46)	188 (73)	196 (65)	168 (69)
difference as % pre-storm 10% 14% 22% 11% 35% KS test: all footprints (sample size r, pre-storm & 2017) - null hypothesis (: angle size r, pre-storm & 2017) - null hypothesis (: angle size r, pre-storm & 2017) - null hypothesis (: angle size r, pre-storm & 2017) - null hypothesis (: angle size r, pre-storm & 2017) - null hypothesis (: angle size r, pre-storm & 2017) - null hypothesis (: angle size r, pre-storm & 2017) - null hypothesis (: angle size r, pre-storm & 2017) - null hypothesis (: angle size r, pre-storm & 2017) - null hypothesis (: angle size r, pre-storm (: ang	2017 mean footprint area (1 stdv)	258 (134)	143 (53)	241 (90)	217 (64)	227 (84)
K8 test: all footprints (sample size n; pre-storm & 2017) – null hypothesis: samples come from same distribution hypothesis (1 = reject nul) 1 (287, 282) 1 (304, 373) 1 (306, 291) 1 (482, 401) 1 (1286, 823) p-value ¹ 4 31E-62 5 05E-04 1.06E-13 1.26E-08 8.86E-55 test attaintic 0.1183 0.1555 0.3138 0.2079 0.3807 parked feas: all footprints (ample size n; pre-storm & 2017) - mUlt hypothesis: samples come from same distribution 1 (1286, 823) 1 (304, 375) 1 (306, 291) 1 (462, 401) 1 (1286, 823) p-value 0.0229 1 (204, 375) 1 (306, 291) 1 (462, 401) 1 (1286, 823) Distribution statistics: altered footprints (pro-storm to 2017) Distribution statistics: altered footprints (pro-storm to 2017) Distribution statistics: altered footprints (ample size n; pre-storm 24% 1 290 4 29% 2 11% 44% 2017 mean altered footprints (sample size n; pre-storm 24% 1 (90, 90) 1 (136, 130) 1 (144, 149) 1 (1278, 329) 2017 mean altered footprints (sample size n; pre-storm 2217) Distribution statistics: namples come from same distribution Pro-store 2 304 2 304 2 304	difference	23	17	53	21	59
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p-value 4.31E-02 5.05E-04 1.9EE-13 1.2EE-08 6.86E-53 test statistic: 0.01183 0.1555 0.3136 0.2079 0.3007 paylace f test: all feotprints (sample size <i>n</i> ; pre-storm & 2017) rull hypothesis: samples come from same distribution 1.1256.65 1.37E-14 1.46E-0 3.72E-44 Comparison of altered building footprints (pre-storm to 2017) Distribution statistics: altered footprints (m) runwer in sample: altered footprints (m) 1.226.62 1.83.601 1.84.62 3.72E-44 2017 mean altered bolprint eas (1 stor) 225 (77) 120.471 169.62 1.83.601 1.84.62 2017 mean altered bolprint eas (1 stor) 226 (77) 120.471 169.622 8.3 2.03 7.2 difference at % pre-storm 2.05.771 120.471 169.622 8.3 2.03 7.2 4.495 2.15 445 Stort altered footprints (sample size <i>n</i> ; pre-storm & 2017) - null hypothesis: samples come from same distribution hypothesis (1 = reject null) 1.04.649 1.000.90 1.163.130 1.149.449 1.6797.379 p-value 2.02600 0.2778<		· · · ·				1 (1295, 823)
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Comparison of altered building footprints (pre-storm to 2017) Distribution statistics: altered footprints (m ¹) 149 1379 number in sample: altered is stay 294 90 136 149 379 pre-storm man footprint area (1 stay) 295 (77) 120 (47) 169 (62) 183 (60) 166 (63) 2017 mean altered footprint area (1 stay) 225 (10) 142 (26) 222 (68) 222 (68) 232 (68) 232 (68) 232 (68) 232 (68) 233 (67) difference as % 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 0.0E-03 1 40E-03 1 63E-13 4 60E-07 9 8.2E-38 Comparison of new building footprints (pre-storm 8 2017) - null hypothesis: samples come from same distribution hypothesis (1 = reject null) 1 (94, 94) 1 (379, 379) p-value 2 0.3E45 0.3E45 0.3E45 0.3E45 0.3E45 0.3E45 0.3E5 <			,			, ,
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number in sample: altered 94 90 136 149 379 pre-storm mean footprint area (1 stdv) 205 (77) 120 (47) 169 (62) 123 (60) 164 (68) 2017 mean altered toolprint area (1 stdv) 224 (101) 144 (26) 222 (83) 239 72 difference as % pre-storm 24% 10% 49% 21% 44% KS test: altered footprints (sample size r; pre-storm & 2017) – null hypothesis: samples come from same distribution 1(49, 194) 1 (149, 149) 1 (379, 379) p-value 2.00E-03 1.40E-03 1.633: 1 (149, 149) 1 (379, 379) p-value 2.00E-03 1.40E-03 1.633: 1 (149, 149) 1 (379, 379) p-value 2.01E-03 0.0024 1.34E-15 2.99E-07 8.82E-38 Comparison of new building footprints (pre-storm to 2017) Distribution satistics: new footprint (m ²) 1.40E-03 1.40E-03 1.40E-03 1.40E-03 1.68E-65	Comparison of <u>altered</u> building foot	prints (pre-storm t	to 2017)			
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difference 50 22 83 39 77 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 1(38, 136) 1(149, 149) 1(379, 379) p-value 2.00E-03 1.40E-03 1.63E-13 4.60E-07 9.12E-34 p-value 2.13E-04 0.0044 1.34E-15 2.99E-07 8.82E-38 Comparison of new building footprints (pre-storm to 2017) Distribution statistics: new footprints (m ²) number in sample: pre-storm image 287 3.04 3.06 4.62 1.295 (295 (291, 104, 291, 104, 294, 106, 106 (292, 190, 104, 294, 102, 104, 106, 201, 1146, 260, 1168 (292, 60) 1.644, 41, 107 37	pre-storm mean footprint area (1 stdv)	205 (77)	120 (47)	169 (62)	183 (60)	164 (58)
difference as % pre-storm 24% 19% 49% 21% 44% KS test: altered footprints (sample size <i>n</i> ; pre-storm & 2017) – null hypothesis: samples come from same distribution https://doi.org/10.1091/j.0001 11(149, 49) 11(39, 379) <i>p</i> -value 2.00E-03 1.40E-03 1.63E-13 4.60E-07 9.12E-34 test statistic 0.2660 0.2778 0.6632 0.3154 0.4459 prevalue 2.016-03 1.40E-03 1.63E-13 4.60E-07 9.12E-34 pothesis (1 = reject null) 1(94, 94) 1(90, 90) 1(138, 136) 1(149, 149) 1(379, 379) <i>p</i> -value 2.13E-04 0.0044 1.34E-15 2.99E-07 8.82E-38 Comparison of new building footprints (pre-storm to 2017) Distribution statistics: new footprints (m ¹) number in sample: pre-storm image 2.87 3.04 3.06 4.62 1.295 0.116ference as % pre-storm image 2.87 3.04 3.06 1.66(6) 1.66(6) 0.0116ference 1.8 1.48 1.07 3.73 1.56	2017 mean altered footprint area (1 stdv)	254 (101)	142 (56)	252 (95)	222 (68)	236 (87)
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 2 006-03 1.40E-03 1.63E-13 4.60E-07 9.12E-34 test statistic 0.2660 0.2778 0.6432 0.3154 0.4459 paired f test: altered footprints (sample size n; pre-storm & 2017) - null hypothesis: samples come from same distribution https://doi.org/10.134E-15 2.98E-07 8.82E-38 Comparison of new building footprints (pre-storm to 2017) Distribution statistics: new footprints (m ²) number in sample: pre-storm image 2.87 3.04 3.06 4.62 1.29E-04 0.017 mean new footprint area (1 stdv) 2.25 (148) 1.26 (46) 1.88 (.73) 1.96 (65) 1.68 (69) 2.017 mean new footprint area (1 stdv) 2.25 (148) 1.26 (48) 1.07 3.7 5.7 difference as % pre-storm 1.4% 2.6% 5.5% 1.9% 3.4% hypothesis (1 = reject null) 0 (287, 9) 1 (3.04, 81) 1 (3.06, 20) 1 (462, 60) 1 (1295, 196)	difference	50	22	83	39	72
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	p-value	0.6956	0.9992	0.2262	0.7223	7.82E-06

[Supplementary Table 2 footnotes]

^a In a two-sample Kolmogorov-Smirnov test, the null hypothesis is that data in the two samples come from the same continuous distribution. The alternative hypothesis is that the two samples are from different continuous distributions. The result of 1 indicates that the test rejects the null hypothesis at the $\alpha = 5\%$ significance level.

^b p is the probability of observing a test statistic as extreme as, or more extreme than, the observed value under the null hypothesis.

^c In a two-sample *t* test, the null hypothesis is that data in the two samples come from independent random samples from normal distributions with equal means and equal but unknown variances. The alternative hypothesis is that the data comes from populations with unequal means. The result of 1 indicates that the test rejects the null hypothesis at the $\alpha = 5\%$ significance level.

^d Hypothetically, total footprint area could change with preferential destruction or removal of buildings of a given size, without otherwise altering footprints of existing buildings. We test for this effect by comparing the mean pre-storm footprint of "surviving" buildings – those present in both images – with the mean pre-storm footprint overall. The only significant difference we find is at Bolivar, where smaller buildings were disproportionately affected. However, the preferential loss of smaller footprints only accounts for a 9% increase in mean footprint size.

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-fam	ily houses comp	leted ^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 (se	ee Supplementary Fig	. 1 & Supplementar	y 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%

^a US Census Bureau, 2016 Characteristics of New Honsing, available at: https://www.census.gov/construction/chars/pdf/c25ann2016.pdf

^b Digitised images were captured in 2017, but most recent year available for national housing characteristics is 2016.

^c Note that in 2015, the mean total floor area was 250 m². Therefore, between 2002–2016 (the maximum span of our analysis, measured at Hatteras/Frisco), the maximum change in mean floor area was 16%.

^d Bold columns indicate direct scaling comparison (e.g., estimated values for Santa Rosa based on scaling factor specific to Santa Rosa).

1 1		1 57
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°

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