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Human-driven atoll island expansion in the Maldives

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Abstract

This study assesses the evolution of 104 inhabited and 82 resort islands across the Maldives between 2004-2006 and 2014-2016 and investigates the contribution of human drivers. Using multi-date satellite imagery, we show that 59.1% of these islands expanded as a result of human intervention, including mainly land reclamation (often associated with harbor development) and the construction of engineering structures. Land reclamation drove island expansion on 93.5% of inhabited islands, whereas land reclamation and/or the effects of engineered structures (especially groins and breakwaters) were involved in 79.2% of the resort islands. Almost 52% of the islands that increased in size experienced growth rates $\geq 10\%$, with 13 inhabited and 6 resort islands exhibiting growth rates $\geq 50\%$. As a result of widespread human intervention, these islands behave very differently from both the documented Pacific islands and the Maldivian islands of Gaafu-Alifu Dhaalu Atoll (most of which are ‘natural’), 15.5% and 19.5% of which underwent expansion over the past decades, respectively. Changes on the islands were driven by political-institutional (one-size-fits-all risk reduction policy based on hard engineering in inhabited islands), demographic (population growth) and socioeconomic (developing and securing outer inhabited islands and post-tsunami tourism growth) factors. The Maldivian island model of ‘reclamation-fortification’ has detrimental impacts on the environment while also questioning the future capacity of the Maldives to face a hard path under increasing risks. Results from the Maldives more broadly offer lessons for other island countries and territories by highlighting the importance of distinguishing between inhabited and exploited and natural islands, and accounting for path dependencies, when designing adaptation solutions.

26 **Keywords**

27 Land area change, shoreline change, human disturbances, socioeconomic development,
28 sustainability, Indian Ocean.

29

30 **1. Introduction**

31 Atolls are ring-shaped reefs that enclose a central lagoon and support islands composed of
32 unconsolidated or poorly lithified carbonate sand and gravel (Woodroffe & Biribo, 2011).

33 Because they are small (generally <1 km²), low-lying (generally <4 m in elevation),

34 comprising unconsolidated material (Woodroffe, 2008), atoll islands are increasingly at risk

35 of marine flooding (Storlazzi et al., 2018; Giardino et al., 2018) and coastal erosion (Shope et
36 al., 2017; Shope and Storlazzi, 2019) under climate change. The risk arises because a range of

37 environmental changes will likely alter the attenuation of wave energy and sediment supply to

38 islands by the reef ecosystem (Quataert et al., 2015; Perry et al., 2018). These changes include

39 sea-level rise (Oppenheimer et al., 2019), increased storm wave heights (Mentaschi et al.,

40 2017; Vitousek et al., 2017), coral reef degradation caused by ocean warming (illustrated by

41 mass coral bleaching caused by the 2015-2016 ENSO event; MacClanahan et al., 2019) and

42 acidification (Gattuso et al., 2015), and local human disturbances (Duvat et al., 2019; Duvat

43 and Magnan, 2019). Since the pioneer study by Webb and Kench (2010), however, increasing

44 assessments of atoll island change over the recent decades proved the prevailing persistence

45 of the land area of individual islands and atolls. This occurred despite higher (i.e. up to

46 5.1 ± 0.7 mm/y in Tuvalu over the 1950-2009 period; Becker et al., 2012) than average

47 (~ 1.8 mm/y for the twentieth century; Church et al., 2013) rates of sea-level rise in some atoll

48 regions. Collectively, these assessments showed that, over the past three to five decades, only

49 11.4% of the 709 documented Indo-Pacific islands decreased in size, whereas 15.5%

50 increased and 73.1% remained stable in area (Duvat, 2019).

51 Multidecadal assessments of atoll island change, however, may not reflect very recent
52 changes in island behavior caused by changes in the magnitude or nature of controlling
53 factors. These factors include, in particular, accelerating sea-level rise (IPCC, 2019) and
54 increasing local human disturbances observed on some atolls (e.g. Duvat et al., 2017; Duvat
55 and Magnan, 2019). To fill this gap, some studies investigated recent (since the mid-1990s or
56 early 2000s) short-term (over 4 to 12 years) changes. These studies, which mainly covered
57 uninhabited (that is, either natural or remote and cultivated) islands, found: (1) higher rates of
58 change for short periods compared to multidecadal time periods (Rankey, 2011; Mann et al.,
59 2016; Duvat and Pillet, 2017); (2) differing trends between atoll regions over recent years,
60 with erosion prevailing on some atolls – e.g. Aranuka in Kiribati (2005-2009; Rankey, 2011)
61 and Wotje in the Marshall Islands (2004-2012; Ford, 2013) – while stability (e.g. Tuvalu,
62 2005-2014; Kench et al., 2018) and accretion (Maiana, Kiribati, 2005-2009; Rankey, 2011;
63 Takapoto, French Polynesia, 1995-2013; Duvat and Pillet, 2017) predominated on others.
64 Changes were mainly attributed, first, to climate variability (e.g., absence of major storm
65 explaining island expansion on Takapoto; Duvat and Pillet, 2017); second, to autogenic
66 processes driving island adjustment to variations in external energy and/or sediment supply
67 (e.g., Maiana; Rankey, 2011; Taku, Papua New Guinea; Mann et al., 2016); third, to human
68 factors, generally activities near villages (e.g., Maiana and Aranuka; Rankey, 2011; Takapoto;
69 Duvat and Pillet, 2017). These studies investigating short-term island changes thus
70 emphasized two key points: first, the high variability of island behavior (erosion, stability,
71 accretion) depending on the local context; and second, the prominent contribution of natural
72 drivers to observed changes.

73 As a complement to these studies, the present study investigates recent short-term (from
74 2004-2006 to 2014-2016) changes in island land area and the drivers of these changes on 104
75 inhabited and 82 resort islands of the Maldives, using satellite imagery. Building upon a

76 previous paper (Duvat and Magnan, 2019) that highlighted the rapidity of human-driven
77 island change resulting from land reclamation, harbor dredging and the construction of coastal
78 protection structures, this study provides new data for the changes in 82 resort islands. It also
79 compares the directions and modes of change of inhabited and resort islands and investigates
80 the main political, demographic and socioeconomic drivers of change on these two types of
81 islands. The present article thus addresses the following questions: (1) To what extent did the
82 Maldivian inhabited and resort islands behave differently from ‘natural’ (that is, unsettled and
83 unexploited, or agricultural) Indo-Pacific and inhabited Pacific atoll islands? (2) What were
84 the main modes and drivers of island areal change on these two types of islands? (3) Which
85 underlying political-institutional, demographic and socioeconomic factors drove island
86 change? (4) What are the future implications of recent changes?

87 **2. The Maldivian context**

88 The Maldives Archipelago extends 890 km between 0°34’S and 6°57’N in the central Indian
89 Ocean. It comprises 21 atolls and 4 oceanic reef platforms supporting 1,149 islands that cover
90 a land area of 227.4 km² (Figure 1; GoM, 2015; Naseer and Hatcher, 2004). Maldivian islands
91 formed on a foundation of lagoonal sediments between 5500 and 2500 yr B.P., depending on
92 atolls (Kench et al., 2005; Perry et al., 2013). Because they are very low-lying (80% of land
93 area <1m above mean sea level) and very small (0.20 km² on average), these islands are
94 especially and increasingly (Wadey et al., 2017) vulnerable to flooding (e.g. flood events of
95 1987, 2007, 2015) under contemporary sea-level rise (Harangozo, 1992; Woodroffe, 2005;
96 Woodworth, 2005; Khan et al., 2010). Between 1950 and 2009, relative sea-level trend values
97 were of 1.3 ± 0.4 and 1.4 ± 0.4 mm/yr at Male’ (North Kaafu Atoll) and Gan (Seenu Atoll),
98 respectively (Palanisamy et al., 2014). Between 1989-1991 and 2015, the rates of sea-level
99 rise accelerated, reaching values of 4.38 ± 0.4 mm/yr and 3.46 ± 0.2 mm/yr at Male’ (1991-
100 2015) and Gan (1989-2015), respectively (Wadey et al., 2017). Because subsidence is low

101 (i.e. of between 0.09 m and 0.16 mm/kyr), it is a minor contributor to relative sea-level rise in
102 the Maldives (Gischler et al., 2018). The Maldivian climate is characterized by a reversal in
103 winds and waves between the northeast monsoon (December to February) and the southwest
104 monsoon (May to September), which causes a reversal in longshore sediment drift and
105 marked changes in shoreline position between seasons (Kench and Brander, 2006; Kench,
106 2012). In addition, the Maldives Islands are affected by tropical depressions forming in the
107 eastern part of the Indian Ocean and by distant-source swells (e.g. May 2007 event)
108 originating from depressions forming in the temperate latitudes of the southern hemisphere
109 (Aslam and Kench, 2017; Wadey et al., 2017).

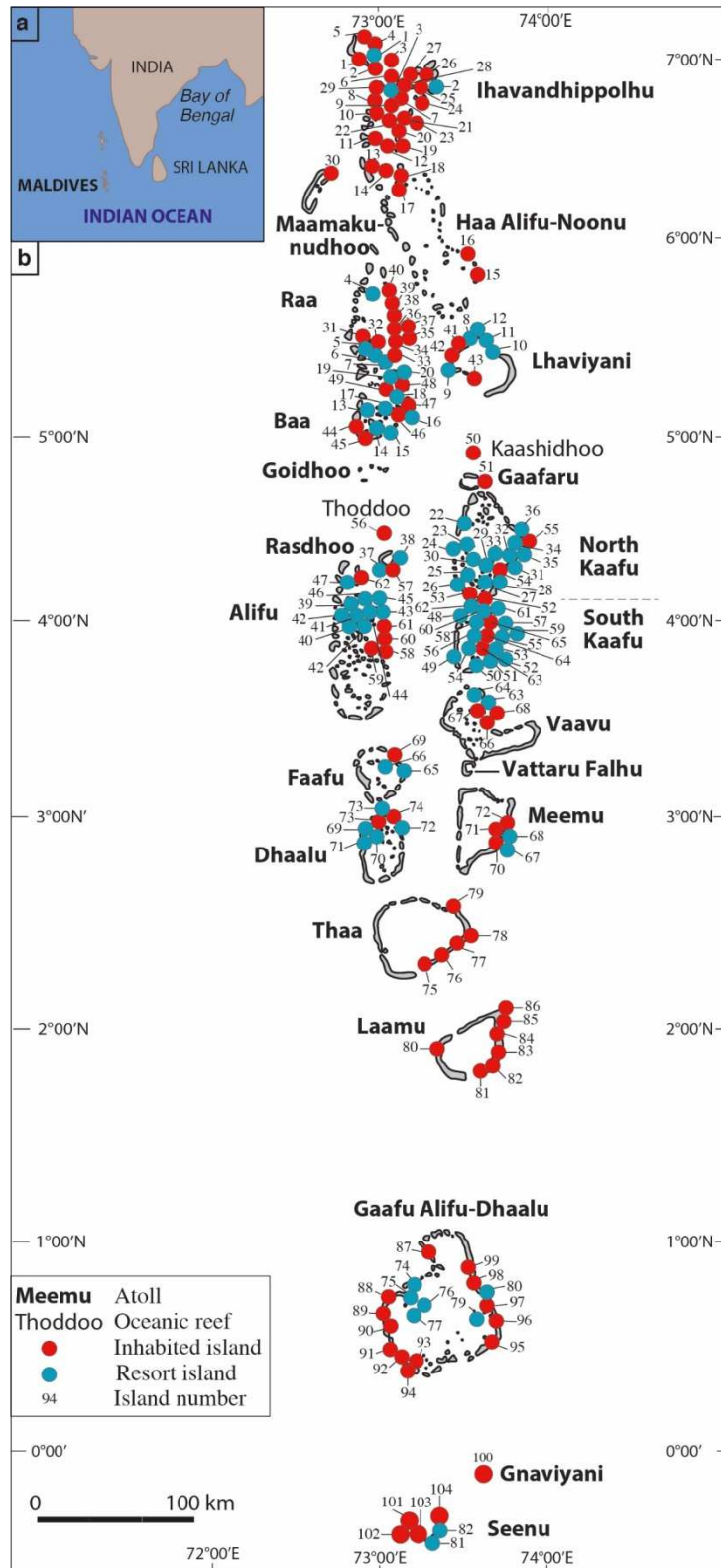
110 In 2016, the Maldives had 188 inhabited islands hosting 402,071 inhabitants and 126 resort
111 islands that received the majority of the 1,286,135 international tourists visiting the country
112 (GoM, 2017). Both population growth (doubling of the population every ~25 years since the
113 1960s; GoM, 2018) and tourism development (increase in total bed capacity by 7% from 2012
114 (25,691 beds) to 2017 (38,737 beds); GoM, 2017) put high pressure on the limited land area
115 of the country and of individual islands. The small size of islands resulted in the scattering of
116 the population into small communities, with 61.7% of the inhabited islands hosting less than
117 1,000 inhabitants in 2014 (GoM, 2015). It also led to a dramatic increase in the number of
118 resort islands (from 126 in 2016 to 142 in 2018) to host continuously growing international
119 tourists (1,484,272 in 2018) (ADB, 2019).

120 Since the 1990s, the small size and the physical instability of the shoreline of these islands
121 have increasingly appeared as a constraint and been addressed through engineering solutions.

122 The latter include raising islands (that is, the creation of artificial elevated islands; Brown et
123 al., 2020), artificially expanding existing islands (Naylor, 2015; Aslam and Kench, 2017;
124 Fallati et al., 2017; Duvat and Magnan, 2019) and armoring and stabilizing shorelines (Shaig,
125 2011; Kench, 2012; Hinkel et al., 2018). Following the 2004 Indian Ocean Tsunami, which

126 killed 82 people and displaced 30,000 people (half of whom had returned to their islands after
127 two weeks) due to the heavy damage to 8,500 houses (Kan et al., 2007; GoM, 2009), island
128 expansion and fortification have been enhanced. The National Population Consolidation
129 Program (NPCP) has led the fortification of the islands. This program was already in place
130 before the Indian Ocean Tsunami but accelerated in response to this event. Following the
131 tsunami, the Seventh National Development Plan was adopted. This plan aimed at
132 concentrating the country's population on a limited number of 'safer' (i.e. raised and
133 protected by engineered structures) islands to better ensure the reduction of risks, while also
134 boosting socioeconomic development through the provision of infrastructure and public
135 facilities (Shaig, 2008; Suppasri et al., 2015).

136 The long-term (1969-2006/2014) study of shoreline changes conducted on Gaafu Alifu-
137 Dhaalu Atoll (see location in Figure 1), which considered 184 islands, most of which are
138 uninhabited, found that 45% of the islands decreased in size while 55% remained stable or
139 increased in area (Aslam and Kench, 2017). Erosional patterns were mainly observed on
140 small islands and interpreted as resulting from changes in the nearshore process regime (i.e.
141 increased sediment mobilization and transport) caused by sea-level rise and/or from a deficit
142 in the sediment budget of islands. Island expansion was attributed principally to land
143 reclamation, which occurred on twelve islands and caused a 93.8 ha increase in land area on
144 the atoll scale. The constructive role of ocean swell on the southern rim of the atoll was a
145 secondary cause of the expansion of islands.



146

147 *Figure 1. Location of the study islands.*

148 *Panels a and b respectively show the location of the Maldives in the Central Indian Ocean and the*

149 *spatial distribution of the 104 inhabited and 82 resort study islands. The latter are numbered from*

150 *north to south. The Supplementary Material uses the same numbering.*

151

152 **3. Materials and Methods**

153 **3.1. Short-term change in the land area of islands**

154 In line with a study analyzing recent land use change in the Maldives (Fallati et al., 2017), we
155 used Google Earth historical satellite images (resolution of 0.5 m) from 2004-06 and 2014-16
156 to assess recent change in the land area of islands. Due to the limited availability of images,
157 which is common on atolls (e.g., Webb and Kench, 2010; Ford and Kench, 2015; Ford, 2013;
158 Aslam and Kench, 2017), we used two different sets (i.e., 2004-2006 and 2014-16) to
159 document the each island at the two periods considered. The limitations encountered were
160 variations in the dates at which the images were taken, even across a given atoll, and cloud
161 cover masking some shoreline sections and islands. To optimize image coverage for a
162 country-wide assessment, we therefore had to use a large number of images. As a result, the
163 initial and final image used differ between islands (see Supplementary Tables 2 and 3). The
164 images allowed assessment of areal change on the islands over the last decade \pm 1 year for a
165 total of 186 islands. Of these, 104 are inhabited while 82 are resort islands. The 186 sample
166 islands are distributed across the entire archipelago (Figure 1), and respectively represented
167 55.3% and 65.1% of the Maldivian inhabited (188) and resort (126) islands in 2016. Together,
168 they covered a land area of ~9,24 ha, which represented ~31.1% of the land area of the
169 country, in 2014-16. At this date, the study islands had an average size of 49.7 ha, and
170 minimum and maximum land areas of respectively 1.4 ha and 693 ha (Supplementary Tables
171 2 and 3).

172 In line with previous studies including inhabited islands (Duvat et al., 2017), we used the
173 stability line as a shoreline proxy. This indicator is appropriate to capture medium to long-
174 term changes on islands change, as it is not affected by seasonal beach change. It corresponds
175 to the vegetation line along natural shoreline and to the outer limit of human-built structures

176 (e.g., seawalls, infrastructures, reclaimed areas) along artificial shoreline. Because many of
177 the Maldivian inhabited and resort islands have artificial shorelines, using this proxy was
178 particularly relevant. Because of the widespread removal of the coastal vegetation, digitizing
179 artificial shorelines was much easier than those on natural islands with overhanging tree
180 branches (Purkis et al., 2016). The only difficulty faced when digitizing the stability line was,
181 on some islands, uncertainty on the status of bare ground— that is, whether it corresponded to
182 reclaimed (i.e., stabilized) area. On the few islands where uncertainty was high, we excluded
183 bare ground from the stabilized part of the island. For each island, we controlled the accuracy
184 of shoreline digitization by checking inter-date consistency, i.e. always providing the same
185 solution to the same problem.

186 We used the stability line to calculate island land area at each date. The two sources of
187 uncertainty included image resolution (0.5 m) and shoreline digitization, estimated to be <1 m
188 based on repeated (n: 10 times) shoreline digitization by the same operator on a representative
189 sample of 20 islands. These uncertainty values are consistent with those obtained in previous
190 studies (Biribo and Woodroffe, 2013; Ford, 2013; Mann and Westphal, 2014). In line with
191 previous assessments (Webb and Kench, 2010; McLean and Kench, 2015; Aslam and Kench,
192 2017; Duvat, 2019; Kench et al., 2018), we used the $\pm 3\%$ threshold to determine significant
193 change. We therefore considered that a change falling within -3% and $+3\%$ was not
194 significant, i.e., indicated areal stability, whereas changes $<-3\%$ and $>+3\%$ respectively
195 corresponded to a reduction and to a gain in island land area.

196 **3.2. Attribution of areal change on islands**

197 **3.2.1. Potential drivers of island areal change**

198 Over the timeframe of analysis, three main drivers may have caused marked island change.
199 These factors include (1) the Indian Ocean Tsunami, for the eight inhabited islands and nine
200 resort islands for which we used pre-tsunami images for the initial date (see Supplementary

201 Tables 2 and 3); (2) the May 2007 and May 2015 swell events (Wadey et al., 2017); (3)
202 human intervention, especially harbor dredging and extension, island artificial expansion and
203 the effects of engineered structures (Aslam and Kench, 2017; Fallati et al., 2017; Duvat and
204 Magnan, 2019). A study investigating the morphological impacts of the Indian Ocean
205 Tsunami on Baa (South Maalhosmadulu) Atoll (see Figure 1) concluded that it had limited
206 impact on the land area of islands on this atoll (Kench et al., 2006). Pertaining to the May
207 2007 and 2015 swell events, available studies reported extensive flooding in highly-exposed
208 western and southern islands, but no erosional impact. We therefore assumed that these events
209 likely caused limited change to island land area over the period of analysis. Because human
210 interventions have influenced changes in the Maldives islands over short periods of time
211 (Kench, 2012; Aslam and Kench, 2017; Fallati et al., 2017; Duvat and Magnan, 2019), we
212 paid special attention to this driver of change.

213 **3.2.2. Contribution of anthropogenic drivers to areal change of islands**

214 Because the Maldives exhibited rapid population growth and tourism development over the
215 period of analysis, we made a special effort to detect the contribution of local human
216 disturbances to island areal change. The latter include land reclamation, harbor development,
217 engineered protection structures, quays and jetties, beach nourishment, vegetation destruction
218 or planting, and dredging in reef flat (Webb and Kench, 2010; Ford, 2012; Hamylton and
219 East, 2012; Biribo and Woodroffe, 2013; Yates et al., 2013; Purkis et al., 2016; Aslam and
220 Kench, 2017; Duvat et al., 2017; Duvat et al., 2019). As in most previous studies, this
221 contribution focused on interpreting images. We first classified islands into two categories,
222 based on the occurrence (coded A) or non-occurrence (coded n.a.) of direct (i.e., visually
223 detectable on images) human disturbances in 2014-2016. Some islands which exhibited
224 human disturbances in 2004-2006 showed no additional human disturbances in 2014-2016
225 (coded A/). We then focused on the islands that exhibited additional human disturbances in

226 2014-2016 compared to 2004-2006, and classified them based on the human disturbance(s)
227 observed (see categories in Tables 1 and 2).

228 We assessed land reclamation on a binary basis: 1. Yes; 2. No. We did not estimate the
229 surface of reclaimed areas because it was difficult to (i) discern pre-2004-06 reclaimed areas,
230 and (ii) establish if land gains were entirely due to reclamation or also to other factors (e.g.,
231 current-driven sediment deposition, beach nourishment). The absence of comprehensive and
232 updated official data on land reclamation did not allow us to overcome these uncertainties. As
233 in previous studies (Aslam and Kench, 2017; Duvat et al., 2017), however, we were able to
234 assess with a high confidence level the occurrence of reclamation and its overall contribution
235 (i.e. high vs. low) to island change.

236 Concerning harbor development, we inventoried “proper” harbors having facilities (i.e., quay,
237 jetty or breakwaters), which are the major infrastructure found on inhabited and resort islands.
238 A proper harbor disrupts longshore and cross-shore sediment transport and deposition
239 (Kench, 2012), which can cause a change in island area over time through a marked increase
240 or decrease in sediment accumulation along the shoreline. In addition, the extension of
241 harbors or dredging in reef flat provides important volumes of materials used for land
242 reclamation (Aslam and Kench, 2017; Duvat and Magnan, 2019). The latter is generally
243 carried out either at harbor ends or in harbor area (qualified as “land reclamation at harbor end
244 or in harbor area”), or along the entire shoreline (qualified as “extensive reclamation”). The
245 large-scale reclamation projects implemented by the Government to support the development
246 of regional centers (meant to reduce inequalities between the capital region and outer islands)
247 and implement the National Population Consolidation Program (Shaig, 2008) were also
248 classified as “extensive reclamation”.

249 The third human disturbance examined was the establishment of coastal (longitudinal or
250 transversal) and marine (longitudinal) engineered protection structures along island shoreline

251 and reef crest. While longitudinal coastal (mostly seawalls and riprap) and marine
252 (breakwaters) structures are common in inhabited islands, groins and foreshore breakwaters
253 are widely used on resort islands (Shaig, 2011). Whereas groins are employed to intercept
254 sediments and to stabilize artificially-nourished beaches, breakwaters are used to reduce wave
255 energy and thereby promote sediment deposition along the shoreline. All of these structures
256 have a high influence on island areal change, by inhibiting sediment deposition, which may
257 lead to land loss (e.g. wave reflection by seawalls), or promoting sediment deposition and
258 thereby causing land gain (e.g. foreshore breakwaters). For each island, we qualitatively
259 assessed changes in the presence of such structures based on the comparison of the two sets of
260 images.

261 Other detectable human disturbances (vegetation removal, jetty construction, beach
262 nourishment, etc.), which played a secondary role in island areal change, were also
263 inventoried based on visual detection.

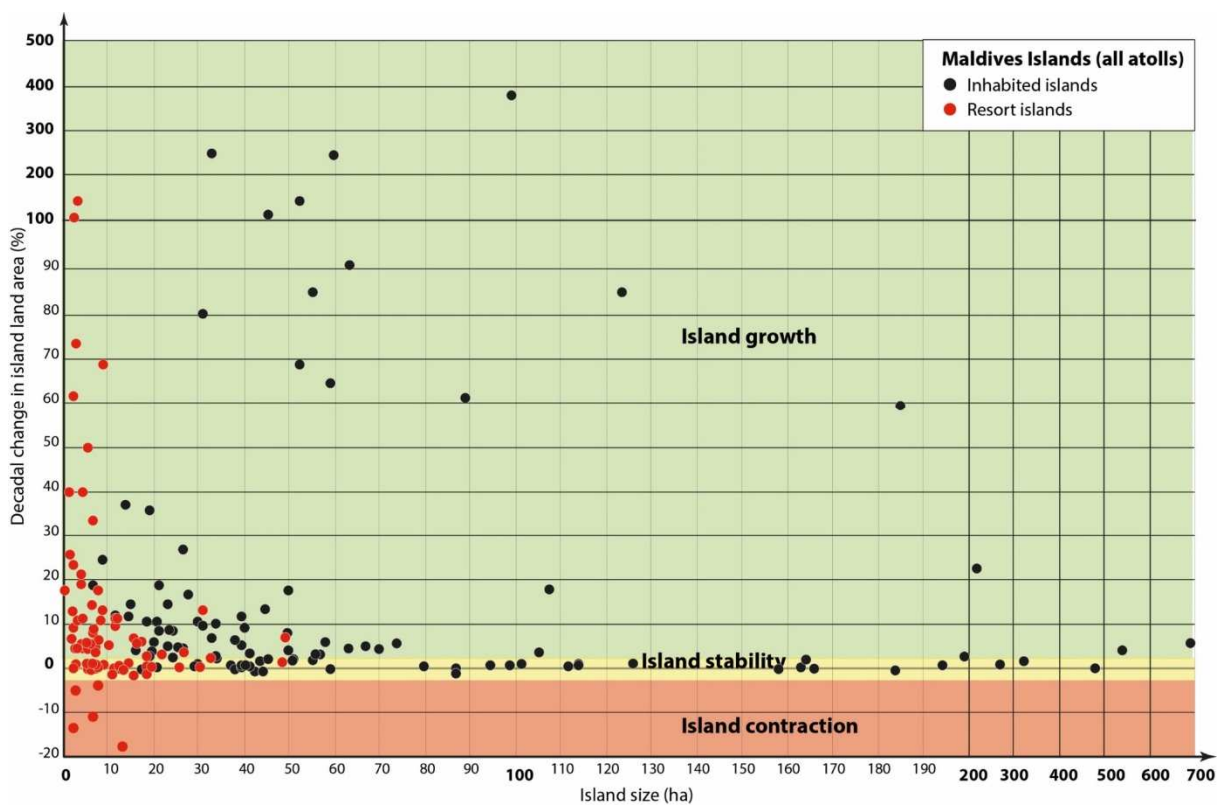
264 **4. Results**

265 **4.1. Change in island area**

266 The sample islands comprise 104 inhabited islands and 82 resort islands, with the former
267 generally much larger than the latter in 2014-16. The proportion of islands exceeding 50 ha in
268 size was respectively nil and of 46.1% for the resort and inhabited sample islands
269 (Supplementary Table 1). In addition, 65.8% of the resort islands had a land area <10 ha in
270 2014-16 against 1.9% of the inhabited islands.

271 Over the past decade, 59.1% of islands (110 islands, including 62 inhabited and 48 resort
272 islands) increased in size ($x \geq 3\%$), whereas 38.2% (71 islands, including 42 inhabited and 29
273 resort islands) were stable and only 2.7% (5 resort islands) decreased in size (Figure 2;
274 Supplementary Tables 2 and 3). These data mean that 97.3% of islands either expanded or
275 were stable in area between 2004-2006 and 2014-2016. The proportions of expanding and

276 stable islands were almost similar for inhabited and resort islands—that is, respectively of
 277 59.6% and 58.5% for expansion, and of 40.4% and 35.3% for stability. The five resort islands
 278 that decreased in size exhibited rates of change comprised between -3.6% (Kanifushi, Baa
 279 Atoll) and -17.7% (Kandoomafushi, South Kaafu Atoll). These islands had areas between 2.4
 280 (islands Nos. 11 and 33 in Supplementary Table 3) and 15.8 ha (island No. 53) in 2004-06.
 281 The results highlight the physical instability of the smallest islands, especially those of less
 282 than 10 ha (Duvat, 2019), which predominantly underwent rapid expansion (Figure 2). A
 283 correlation between island size and the amplitude of change also showed the smallest islands
 284 undergoing the largest changes. Importantly, 51.8% of the islands that increased in size (57
 285 islands out of 110, including 33 inhabited and 24 resort islands) experienced growth rates
 286 $\geq 10\%$, with 13 inhabited and 6 resort islands exhibiting rates $\geq 50\%$.



287
 288 *Figure 2. Decadal change in island land area on 186 inhabited and resort islands in the*
 289 *Maldives.*

290 *The yellow area corresponds to areal stability ($3% < x < -3%$), while the green and red areas*
291 *respectively indicate island expansion ($x \geq 3%$) and contraction ($x \leq -3%$). The sample islands,*
292 *including islands >100 ha, predominantly exhibited growth (110 islands; 59.1%) and secondarily*
293 *experienced stability (71 islands; 38.2%). Only 5 small resort islands showed contraction.*

294

295 **4.2. Contribution of human activities to island areal change**

296 More than 90% of the inhabited islands (94 out of 104) and 85% of the resort islands (70 out
297 of 82) exhibited additional human disturbances in 2014-16 compared to 2004-2006. Direct
298 human disturbances contributed to island areal change on 98.1% of inhabited islands (i.e. 102
299 islands out of 104; Table 1) and 93.9% of resort islands (i.e. 77 islands out of 82; Table 2).
300 Only 8.1% of islands (7 islands) experimented areal change without any detectable human
301 influence.

302 The main types of human disturbances involved in the areal change of islands were different
303 between inhabited and resort islands (Tables 1 and 2). Land reclamation occurred on 96.7%
304 (89 out of the 92) of the inhabited islands that experienced additional human disturbances in
305 2014-16 compared to 2004-06. On 91.0% (81) of these islands (A1 to A5 in Table 1), land
306 reclamation was associated with the dredging or extension of an existing harbor, or with the
307 dredging of one or more new harbor(s) in the island reef flat. Land reclamation occurred
308 either in the harbor area only (49 islands; A1, A2, A4), or on a larger scale, i.e. along most of
309 the harbor coast or even along other shoreline sections (32 islands; A3, A5). Except for the
310 two islands of Seenu Atoll that exhibited areal gains of 8.0 ha and 24.0 ha (islands Nos 101
311 and 104, respectively; Supplementary Table 2), the islands that experienced land reclamation
312 in harbor area only exhibited areal gains of less than 4 ha. Areal gains due to land reclamation
313 in harbor area caused a maximum island expansion of 11.6% (island No 76). In contrast, the
314 islands that experienced extensive land reclamation (i.e. including outside the harbor area)
315 showed much greater areal gains (i.e. >20 ha for 12 islands, with a maximum gain of 76.8 ha

316 for island No75; Supplementary Table 3). Gains in land area were $\geq 10\%$ of initial island area
317 for 33 of these islands (31.7%). Thirteen of these islands (12.5%) experienced gains $\geq 50\%$,
318 with 5 islands (4.8%) even experiencing gains $\geq 100\%$ (Nos 41, 44, 74, 75 and 79, with a
319 maximal value of 384% for island No 75). Most atolls had islands exhibiting such high
320 growth rates. All in all, land reclamation (either associated with harbor dredging or not) was
321 involved in 58 out of the 62 islands that expanded over the period of analysis. These results
322 emphasize the major role of harbor dredging in providing the materials needed for artificially
323 expanding inhabited islands. This means that the considerable and unprecedented effort made
324 by the Government of the Maldives to equip these islands with harbors largely explains the
325 widespread (i.e. in most atolls) and dramatic island expansion observed.

326 Among the 82 resort islands sampled in 2014-16, 29.3% (24 islands) were still unexploited in
327 2004-06. These data reflect the rapid growth of tourism between 2004-06 and 2014-16 (101
328 resort islands in 2011; 115 in 2015; 126 in 2016; GoM, 2017). On resort islands, human
329 intervention consisted of the establishment of hard protection structures along island shoreline
330 (noted on 41 islands; Table 2 and Supplementary Table 3) and/or on island reef flat (foreshore
331 breakwaters, noted on 17 islands). Among the former, 19 showed no other detectable human
332 intervention, while 22 also experienced other disturbances such as land reclamation, dredging
333 or the construction of a quay or jetty. Human intervention secondly consisted of land
334 reclamation, which affected 39.0% of islands (32 islands). Land reclamation was associated
335 with harbor extension or dredging on 8 islands, but also noted on 23 islands where no harbor
336 works were present. On these latter islands, we often observed sediment extraction from the
337 island reef flat or lagoon, and sometimes associated with beach nourishment (see A11 in
338 Table 2). Although no quantitative data are available on sediment extraction, we assume that
339 the latter has significantly contributed to island growth. Focusing on the 48 resort islands
340 (58.5% of the total) that exhibited expansion over the period of analysis, we note that

341 respectively 14 (29.2%) and 13 (27.1%) experienced land reclamation and the construction of
 342 new protection structures, whereas 11 additional islands (22.9%) exhibited both types of
 343 interventions. Such works were also carried out on islands that remained stable or that
 344 decreased in size. Among the 29 resort islands that exhibited areal stability, for example, three
 345 experienced land reclamation whereas 13 had new protection structures. Likewise, two out of
 346 the five islands that decreased in size were equipped with protection structures. The maximum
 347 areal gain, noted on two islands (Nos 36 and 50 in Supplementary Table 3), reached up to
 348 3.7 ha. Gains in land area were $\geq 10\%$ of initial island area for 24 islands (50.0% of expanding
 349 resort islands). Six of these islands experienced gains $\geq 50\%$, with two islands even exhibiting
 350 gains $\geq 100\%$ (maximum value: 140%, No 52). These findings emphasize the major
 351 contribution of rapid tourism growth to island areal gain, even though resort islands
 352 experienced smaller areal gains compared to inhabited islands. The proportion of islands
 353 exhibiting high growth rates was higher in the central tourist atolls of North Kaafu, Alifu and
 354 South Kaafu, compared to other atolls. On South Kaafu Atoll, for example, 10 out of the 14
 355 resort islands experienced gains $\geq 10\%$, 4 of which even exhibiting rates $\geq 50\%$.

356

357 Table 1. Human disturbances involved in inhabited island areal change between 2004-2006
 358 and 2014-2016 (see Supplementary Table 2 for details).

Driver	Number of islands affected
A1. Land reclamation at harbor end or in harbor area	5
A2. New harbor(s) dredged in reef flat associated with land reclamation at harbor end or in harbor area	32
A3. New harbor(s) dredged in reef flat associated with extensive land reclamation	16
A4. Harbor extension with limited or moderate land reclamation at harbor end or in harbor area	12
A5. Harbor extension with extensive land reclamation	16
A6. Extensive land reclamation	8
A7. Other changes (e.g. breakwater construction or extension)	3
Sub-total	92
n.a. Inhabited island exhibiting no significant human disturbance in 2014-2016	2
A/ Inhabited island exhibiting influential human disturbances in 2004-2006 showing no additional human disturbances in 2014-2016	10
Total	104

359

360 *Ninety-two inhabited islands (88.46%) exhibited areal change due to human disturbances between*
 361 *2004-2006 and 2014-2016. This table emphasizes the major contribution of harbor dredging*
 362 *associated with land reclamation in inhabited island areal change.*

363

364 Table 2. Human disturbances involved in resort island areal change between 2004-2006 and
 365 2014-2016 (see Supplementary Table 3 for details).

Driver	Number of islands affected
A1. Land reclamation at harbor end or in harbor area	4
A2. New harbor dredged in reef flat associated with land reclamation at harbor end or in harbor area	3
A3. Extensive land reclamation	6
A4. Engineered protection structures (breakwaters, groins, seawalls)	19
A5. Land reclamation + engineered protection structures	14
A6. New harbor dredged in reef flat associated with land reclamation at harbor end or in harbor area + engineered structures	1
A7. New harbor dredged in reef flat	1
A8. Dredging in reef flat	1
A9. Dredging in reef flat + engineered structures	6
A10. Dredging in reef flat + land reclamation	3
A11. Beach nourishment*	2
A12. Vegetation destruction	2
A13. Quay or jetty	2
A14. Quay or jetty + engineered protection structures	1
Sub-total	65
n.a. Resort island exhibiting no significant human disturbance in 2014-2016	5
A/ Resort island exhibiting influential human disturbances in 2004-2006 showing no additional human disturbances in 2014-2016	12
Total	82

366 *This table highlights the major contributions of land reclamation (A1, A2, A5, A6, A10, A15) and*
 367 *engineered protection structures (A4, A5, A6, A9, A14, A15) in resort island areal change. * Under-*
 368 *estimated due to detection difficulties.*

369

370 **4.3. Direction and modes of change in inhabited and resort islands**

371 Beyond the general trend described above, inhabited islands exhibited contrasting degrees of
 372 human modification over the decade of analysis. Whilst land reclamation was the main driver
 373 of change on these islands, its influence varied substantially between islands. Four types of
 374 situations are possible. First, islands experience only limited and localized (i.e. in harbor area)
 375 land reclamation that did not generate any gain ($x < 3\%$) in land area (e.g. +0.9% in the case of

376 Kodey; Figure 3a). These islands represent 36.7% of the inhabited islands affected by land
 377 reclamation. Second, islands exhibit a moderate to significant ($3\% \leq x \leq 10\%$) gain in land area,
 378 which represent 26.7% of reclaimed islands. Third, islands exhibit a marked areal gain (e.g.
 379 +17.9% for Ukulhas; Figure 3a) due to extensive land reclamation associated with harbor
 380 dredging. These islands represent 22.2% of reclaimed islands. Fourth, islands exhibit total
 381 transformation in shape, size and sometimes position on the reef flat, following extensive land
 382 reclamation, like Thulhaddhoo and Vilufushi (Figures 3c and 3d). These islands are present in
 383 nine atolls and represent 14.4% of inhabited islands affected by land reclamation.
 384 Thimarafushi (Thaa Atoll, No 75) was considerably extended for airport construction between
 385 2010 and 2012 (+76.8 ha, from 20 ha in 2005 to 96.8 ha in 2016), for example, which led to
 386 the incorporation of the nearby islet of Hiriyanfushi.



387
 388 *Figure 3. Patterns of change on inhabited islands.*

389 *a shows an island that underwent limited shoreline and areal change (+1 ha corresponding to a gain*
390 *of 0.9%). The main change observed was localized lagoon shoreline advance caused by harbor*
391 *dredging-induced land reclamation. b shows an island that experienced marked changes (+3.2 ha*
392 *corresponding to a gain of 17.9%), as a result of harbor extension and associated extensive land*
393 *reclamation. c and d show islands that underwent dramatic shoreline and areal change (+22.5 ha*
394 *corresponding to a gain of 105.1% for Thulhaadhoo; +42 ha corresponding to a gain of 241.4% for*
395 *Vilufushi) due to extensive land reclamation. On such islands, the entire shoreline is now artificial, i.e.*
396 *fixed by engineered structures.*

397

398 Over the period of analysis, resort islands also experienced various degrees of human-induced
399 areal change. Some islands underwent limited change in area and configuration. This occurred
400 both on islands that were already exploited in 2004-06 and affected by additional human
401 disturbances in 2014-16 (e.g. Alidhoo; Figure 4b), and on islands that were natural in 2004-06
402 and then became a resort island (e.g. Havoddaa, Figure 4c). At the other end, some resort
403 islands have undergone marked changes in area and configuration, as a result of the
404 cumulative effects of land reclamation, additional coastal protection structures and beach
405 nourishment. Halaveli (No44) expanded by 40.0%, for example, due to land reclamation and
406 increased sediment deposition. Extension of foreshore breakwaters along the reef crest caused
407 the sediment deposition, with the breakwaters now forming a nearly-continuous protection
408 around the island (Figure 4a). In some cases, extensive land reclamation caused a marked
409 increase in land area and a complete change in the shape of the islands, as illustrated by
410 Maadhoo, South Kaafu Atoll (+140%; Figure 4d). The islands that expanded through land
411 reclamation were often equipped with groins, meant to stabilize beaches (Figures 4a and 4d).
412 The impacts of tourism development on island areal change were highly variable, with some
413 of the most recently-developed resort islands (e.g. Maadhoo, opened in 2016; Figure 4d)
414 undergoing total transformation.



415

416 *Figure 4. Patterns of change on resort islands.*

417 *a shows an island that experienced major shoreline and areal change (+1.2 ha corresponding to a*
 418 *land area gain of 40%), as a result of land reclamation. The establishment of foreshore breakwaters*
 419 *has increased sediment deposition on the reef flat and at the coast, which has allowed the development*
 420 *of the coastal vegetation. b illustrates limited shoreline and areal change (+0.3 ha corresponding to*
 421 *an areal gain of 2.2%). It also shows the use of foreshore breakwaters to protect water bungalows*
 422 *from waves. On this island, breakwaters have so far not caused major changes to island*
 423 *configuration. c shows that despite its change from natural to a resort island in 2015, Havoddaa*
 424 *(8.4 ha) experienced limited shoreline change and no areal change to date. d shows the land-*
 425 *reclamation-induced expansion of Maadhoo (3.6 ha in 2016; + 140%). c and d respectively illustrate*
 426 *environment-friendly and environmentally-destructive tourism development.*

427

428 **5. Discussion**

429 **5.1. Originality of the trajectory of change of inhabited and resort Maldivian islands**

430 Study islands behaved very differently from both inhabited Pacific atoll islands and
431 Maldivian rural and unsettled islands, which mainly exhibited stability over the past decades.
432 Fifty-nine percent of study islands underwent expansion, against 15.5% of the documented
433 Indo-Pacific 709-island sample mainly comprising rural and natural islands (Duvat, 2019) and
434 19.5% of the 184 predominantly unsettled Gaafu Alifu-Dhaalu islands (Aslam and Kench,
435 2017). In one decade, 31.7% and 50.0%, respectively, of the inhabited and resort islands that
436 increased in size experienced growth rates $\geq 10\%$. Respectively, 21% and 12.5% of these
437 islands exhibited growth rates $\geq 50\%$. These rates contrast with those of naturally accreting
438 islands, which rarely exceed 10%. Land reclamation contributed to island expansion on
439 93.5% of inhabited islands and 52% of resort islands.

440 **5.2. Political-institutional, demographic and socioeconomic drivers of inhabited island**
441 **expansion**

442 Over the period of analysis, the M.A. Gayoom (1978-2008, Progressive Party of Maldives)
443 and A. Yameen (2013-2018, Progressive Party of Maldives) administrations – shortly
444 interrupted by the 2008-2012 M. Nasheed Presidency (Maldivian Democratic Party) – gave
445 priority to socioeconomic development to reduce tensions between the capital region
446 (including Male’, Hulhumale’ and Villingili islands) and peripheral atolls. These tensions
447 result from high disparities with regards to access to staple goods, jobs, education and health
448 facilities (Arnall and Kothari, 2015; Hirsch, 2015; Speelmann et al., 2016). To reduce these
449 tensions and especially put an end to chronic shortages of products affecting human well-
450 being and economic activity in outer atolls (Hirsch, 2015), the Government made
451 unprecedented nation-wide investments in harbor development between 2004-2006 and 2014-
452 2016. These investments also aimed at repairing the tsunami-induced damage caused to
453 harbors and jetties on 104 inhabited islands (GoM, 2009). Harbor development provided large

454 amounts of construction materials used to expand densely populated islands through land
455 reclamation (Naseer, date unknown). This investment, in turn, led to increased shoreline
456 armoring due to (i) the stabilization of newly-reclaimed areas by protection structures, and (ii)
457 the erection of defenses in areas adjacent to harbors and affected by shoreline destabilization
458 (Shaig, 2011; Kench, 2012).

459 Political-institutional factors likely explain why one single island development model (the
460 ‘reclamation-fortification model’) was implemented across the whole archipelago. The
461 centralization of power at the highest levels of government leads to the standardization of risk
462 reduction action on the ground. The non-consultation and non-involvement of local level
463 governments, NGOs and concerned communities in decision-making and implementation
464 reduce opportunities for the diversification of experiments and explain the spread of the
465 ‘reclamation-fortification model’ across the whole country. This model, which originates in
466 the initial choice of hard protection by Maldivian politicians, has since then persisted due to
467 institutional inertia (Ratter et al., 2019, p. 175). Shoreline and island fortification generally
468 meet the preference of inhabitants, who view hard engineering as a “true” and permanent
469 solution providing value-for-money (Shaig, 2011). This preference comes from: (1) the
470 inhabitants’ view that the Government is responsible for and should therefore fund coastal
471 protection; (2) the fact that the Government funds hard protection, but not soft measures,
472 which reinforces the view that hard engineering is the only appropriate solution; (3) the
473 disproportionate damage caused by the 2004 Indian Ocean Tsunami to unprotected outer
474 islands compared to armored Male’, which reinforced this view (Shaig, 2008; Sovacool,
475 2012; Ratter et al., 2019).

476 Since the 1980s, the socioeconomic tensions highlighted above have caused massive
477 population movements from outer atolls to the capital area, including Male’ (128,768
478 inhabitants in 2016) and, since the mid-2000s, the artificial and raised island of Hulhumale’

479 (from 2,866 in 2006 to 15,769 inhabitants in 2014), created to meet housing, commercial and
480 development needs of the capital area (Mohit and Azim, 2012). These population movements
481 have led to the continued population and economic growth of the Male' region, which has
482 further exacerbated the preexisting socioeconomic gap and thus reinforced the attractiveness
483 of the capital region (Speelmann, et al., 2016). To reduce these population movements, the
484 Government has, since the 1960s, designed successive population consolidation policies
485 aimed at regrouping the population in a limited number of large islands that would provide
486 public facilities and economic opportunities (Shaig, 2008). These policies have all failed until
487 the 2004 Indian Ocean Tsunami, which opened a 'policy window' for population
488 consolidation through the Safe Island Development Program (SIDP) aimed at (i) improving
489 public service delivery (including transportation, through harbor and airport development)
490 and social development, (ii) increasing economic growth, and (iii) reducing environmental
491 vulnerability, on a limited number of outer islands. Even though financial and technical
492 constraints have limited the implementation of the SIDP, this program is responsible for the
493 transformation and high expansion rates of those islands designated regional or growth
494 centers. This process is illustrated by Vilufushi, Thaa Atoll (Figure 3d), which is one of the
495 five new regional centers of the country (Plewa, 2018). During the tsunami, Vilufushi
496 suffered widespread destruction and its population was evacuated to nearby Buruni. Its
497 reconstruction included its expansion through reclamation (+42 ha; + 241.4%), the armoring
498 of the entire shoreline and the construction of 309 new houses, which allowed the population
499 to be back on the island in May 2009 (GoM, 2009). This new enlarged and safer island, aimed
500 at acting as an attractive regional center, illustrates the emergence of a new inhabited island
501 type, represented by thirteen islands in this study.

502 **5.3. Post-tsunami tourist recovery drives resort island change**

503 By causing an unprecedented economic crisis – with damages equaling to 62% of the
504 country’s GDP, making the Maldives the hardest hit country in Asia (Luetz, 2017) – the
505 Indian Ocean Tsunami pushed for the prioritization of economic recovery through tourism
506 growth. Twenty-one resort islands totaling 4,000 beds (23% of the total) were devastated and
507 closed after the Tsunami, which had all reopened by April 2009. To speed up the recovery
508 process and generate additional economic opportunities, many new resorts have been
509 authorized after the tsunami (GoM, 2009), which explains the marked increase in the number
510 of resort islands and engineering works contributing to island expansion between 2004-06 and
511 2014-16. Over this period, tourism recovery and growth led to the construction of airports in
512 peripheral atolls, which required the extensive reclamation of some inhabited islands.
513 Thimarafushi Island, Thaa Atoll (No 75; Supplementary Table 2), illustrates the process of
514 extensive reclamation (+76.8 ha) for constructing an airport.

515 **5.4. Implications of the Maldivian ‘reclamation-fortification island model’**

516 The ‘reclamation-fortification island model’ raises environmental and financial issues, with
517 major implications on the security of future populations. First, it compromises (through reef
518 flat destruction, obstruction of sediment transport and annihilation of coastal accommodation
519 space) the capacity of the ‘self-maintained’ (Temmerman et al., 2013) reef-island system to
520 adjust to sea-level rise through vertical growth, causing a path-dependency to engineering
521 (Duvat and Magnan, 2019). In turn, this path-dependency to engineering questions the future
522 capacity of the Maldives to ensure (technically and financially) the maintenance and
523 upgrading of defense structures to contain increasing sea-related risks. Internal funding will
524 be increasingly challenged by the impacts of increasing disaster frequency on tourism
525 revenues (flood-related and potentially Covid-like), while international funding is uncertain.
526 Lastly, the accelerated human-induced degradation of the reef ecosystem will amplify the
527 negative impacts of climate change on food supply. The impacts are all the more urgent as

528 fish consumption is key to population diet (per capita consumption of 181 kg/yr; Hohne-
529 Sparboth, 2013), with consumption of reef fish increasing at household level (Sattar et al.,
530 2014).

531

532 **Conclusions**

533 In summary, analysis of 104 inhabited and 82 resort islands across the Maldives archipelago
534 produced the following answers to the research questions posed. First, this study shows that
535 the Maldivian inhabited and resorts islands behave very differently from both ‘natural’ Indo-
536 Pacific and Pacific inhabited atoll islands between 2004-2006 and 2014-2016. Fifty-nine
537 percent of the former underwent expansion, compared to 15.5% of the documented Indo-
538 Pacific 709-island sample (Duvat, 2019) and 19.5% of the predominantly natural islands of
539 Gaafu-Alifu Dhaalu Atoll, Maldives (Aslam and Kench, 2017). Respectively, 31.7 and 50.0%
540 of expanding inhabited and resort islands experienced growth rates $\geq 10\%$, with respectively
541 21 and 12.5% of these islands even exhibiting growth rates $\geq 50\%$, while naturally accreting
542 islands show growth rates $< 10\%$.

543

544 Second, results show that the main modes of areal changes on the islands were different
545 between inhabited and resort islands. Land reclamation, often associated with harbor
546 development, drove island expansion on 93.5% of inhabited islands, whereas land
547 reclamation and/or the effects of engineered structures (especially groins and breakwaters)
548 were involved in 79.2% of resort islands.

549

550 Third, the factors underlying the expansion of islands were different between these two
551 islands types. The implementation of one single island model, the ‘reclamation-fortification
552 island model’, in inhabited islands was likely due to a combination of political-institutional

553 (effort made by the Government to develop and secure outer islands), demographic
554 (population growth) and socioeconomic (reduce disparities between the capital region and
555 outer islands) factors. Simultaneously, the unprecedented economic crisis caused by the
556 Indian Ocean Tsunami pushed for the prioritization of economic recovery through tourism
557 growth over the 2004-2006/2014-2016 period. This process was achieved through the
558 expansion of already operating and the development of new resort islands, which encouraged
559 airport development, all of which pushed for land reclamation and increased use of
560 engineered structures.

561

562 Fourth, this study highlights the long lasting implications of the ‘reclamation-fortification
563 island model’, which compromises the capacity of the reef-island system to naturally adjust to
564 sea-level rise. This limitation creates a path dependency to engineering (which has heavy
565 technical and financial implications under increasing risks implying structure maintenance
566 and upgrading over time). It is also detrimental to local, including reef-based, fish supply,
567 which plays a major role in outer island population diet.

568

569 Finally, results from the Maldives Islands provide lessons for other island countries and
570 territories worldwide. They show that in these settings, densely urbanized and developed
571 coastal areas may have undergone rapid and marked physical transformation over the past
572 decade, as a result of the widespread use of engineering solutions to face both climate (i.e., to
573 reduce increasing coastal risks) and socioeconomic (i.e., to face population growth and boost
574 economic development) challenges. The underlying endogenous (i.e., political-institutional,
575 socioeconomic, cultural, etc.) and exogenous (e.g., impact of the Indian Ocean Tsunami on
576 international tourism in the Maldives) drivers involved in the widespread use of engineering
577 solutions have, at least in some islands, already generated a hard path dependency that

578 reduces the range of options available to face future climate challenges. Such results advocate
579 first, for distinguishing between developed (i.e., inhabited and exploited) and natural islands,
580 and second, for accounting for path dependencies, when designing adaptation strategies. This
581 means that adaptation solutions must absolutely be island-specific in these settings.

582

583 **Data availability**

584 All data generated during this study are included in this published article and its
585 Supplementary Material.

586

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