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Kench, Thompson, Ford, Ogawa and McLean

Appendix DR1 Methods

The study examined the changes in planform characteristics of 29 islands located on Funafuti's atoll rim (Figure DR1) based on comparative analysis of geological maps, historical aerial photography and satellite imagery spanning 118 years (Table DR1, DR2). The island sample comprises 8 sand islands, 9 gravel islands and 12 mixed sand gravel islands. The morphology and sediment character of the islands have previously been described by McLean and Hosking (1991). Two of the islands (Amatuku and Fogafale) are inhabited.

Critical for construction of the centennial-scale analysis, were geologic surveys of islands in the atoll undertaken in 1897 during the second of three Royal Society of London expeditions to Funafuti in 1896-1898 (Bonney, 1904). As noted by the expedition: "*Geological surveys have been made of the various islets of the atoll, in sufficient detail to admit of maps being constructed from them, which it was hoped would be of use later in the study of any changes which the islets might subsequently undergo, as well as in supplying information as to the latest geological history of the atoll*" (David and Sweet, 1904). The maps present detailed planform characteristics of each island including distinct geomorphic units and vegetation classes as well as topographic cross-sections across each island. The surveys are reported to have a closure error of approximately 2.0 m. As recently noted: "*There is no doubt that the maps of Funafuti remain the most comprehensive and detailed illustrations of the surficial morphology of any atoll…*" (Spencer et al., 2008). Consequently, the existence of the geological maps provides an unprecedented opportunity to examine planform changes in islands that span more than a century.

Figure DR1. Location of Funafuti atoll, Tuvalu (A) and location of study islands in Funafuti Atoll (B).

In addition to the 1897 geological maps aerial photographs that cover the study islands were available from 1943 (incomplete coverage), 1971 and 1984. The aerial photographs used all had a scale of < 1:25,000. Once scanned these images were enhanced to maximise contrast of features. The dataset also included a mosaic of Quickbird (QB) satellite imagery captured in 2005 and panchromatic WorldView 1 (WV1) satellite imagery captured in 2013.

Image processing

All data sources were imported into a Geographic Information System (ArcMap) for image geo-referencing and comparison using a number of techniques. The WGS 1984 UTM zone 60S coordinate system forms the common coordinate system across the analysis. WV1 satellite imagery captured in 2013 provided the sources of ground control points for georeferencing aerial photographs and QB satellite imagery. Given the paucity of stable anthropogenic features on reef islands, a range of natural features such as cemented conglomerate, beachrock and coral blocks were used as ground control points. Images were georeferenced in ArcMap and transformed using a second order polynomial transformation. The georeferencing errors (Root Mean Square) errors varied between photographs and ranged from 0.41 m to 2.02 m.

Geological maps were scanned at 900 dpi and imported into ArcMap. Due to the inability to confidently detect adequate control points on geological maps they were not georeferenced. Rather maps were sized to their set scale and rotated to true north for analysis of island orientation and area.

Shoreline Interpretation and Analysis

For each time period the perimeter of the island was determined by digitizing the edge of vegetation as a line feature. The edge of vegetation identifies the boundary of the relatively stable vegetated island core in the short-term and avoids spatial ambiguity in defining low or high water mark or temporal fluctuations in beach position (Webb and Kench, 2010). The edge of vegetation is widely used as a proxy for shoreline position within shoreline change studies in atoll settings (Webb and Kench, 2010, Ford, 2013, Yates et al., 2013). The edge of vegetation is readily identifiable in nearly all imagery, regardless of image colour and contrast and irrespective of environmental conditions such as glare and waves all of which can impede interpretation of the toe of beach. The edge of vegetation was digitised at a fixed scale by a single operator within ArcMap.

The 1896-98 dataset are geological maps and provide details primarily on landform units as denoted by topography, degree of lithification and composition of sediments (Figure DR2A). However, descriptions also indicate whether each unit also had vegetation cover (Figure DR2B). The edge of vegetation was therefore, determined by encompassing all units in which vegetation had been identified (units L.6 to L.8.B) and those encompassed by these units (Figure DR2C). While we have high confidence in the scale and orientation of the 1896-1898 island surveys it was not possible to accurately overlay 1896-98 shorelines due to a lack of ground control points in the maps.

Digitised polygons allowed the island area in each time period to be calculated. Changes in the planform characteristics (configuration and position) of islands were examined by overlaying the edge of vegetation polygons for each island. Analysis allowed relative erosion and accretion around different sectors of the island to be determined and whether the island

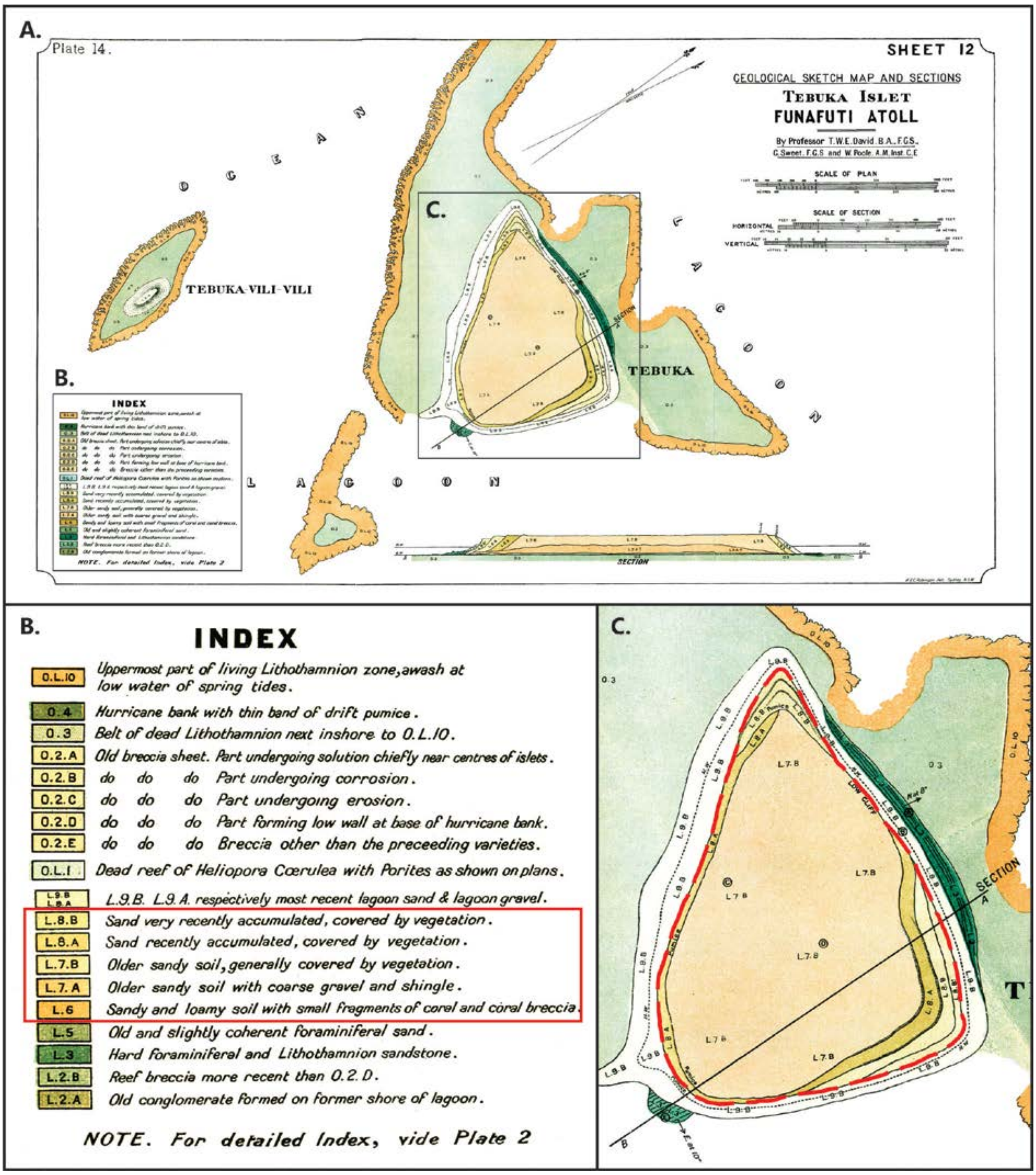

Figure DR2. Method used to define the edge of vegetation from geological maps. A) An example of the geological maps, Plate 14: Tepuka Islet. B) Notes that accompanied the geological units. Red box denotes those units that describe island components with vegetation cover. C) Expanded view of Tepuka Island showing the digitised edge of vegetation line (red dashed line) encompassing the units identified in B.

had substantially shifted its position on the reef surface. As noted above it was not possible to accurately overlay all 1896-98 polygons due to a lack of GCP points in the earlier maps. However, in some cases the 1896-1898 shoreline was overlain by aligning the centroid of the 1896-1898 island polygons with the average position of the centroid of post-1943 island polygons. In other cases uncertainties in overlays allowed only broadscale adjustments in island planform characteristics to be evaluated.

Shoreline Uncertainty

Following Ford (2013) three sources of uncertainty were considered when calculating the positional uncertainty in edge of vegetation interpreted from remote imagery, being: rectification (RMS georeferencing error), pixel size and digitizing errors. Digitizing error was calculated as the standard deviation of shoreline position from repeated digitization of the same section of coast by a single operator. Total shoreline error (Te) was calculated as the root sum of all shoreline position errors. Shoreline errors are summarised in Table DR1.

The Digital Shoreline Analysis System (DSAS) is a widely used analytical tool for measuring changes in planform positions of vectorized shorelines (Thieler et al., 2009). DSAS runs as an extension for ArcMap. DSAS analyses change by recording the intersection of shorelines and transects cast perpendicular to a user-generated baseline. In this study transects were cast every 10 m along the baseline. Two measures of island change are utilised in this study. First, the Shoreline Change Envelope (SCE), the distance between the most landward and most seaward shoreline. Second, the distance between the oldest and most recent shoreline was calculated, known as the Net Shoreline Movement (NSM). Where a continuous shoreline forms an unbroken island perimeter area was calculated by converting shorelines to polygon features in ArcMap.

Unlike shoreline change analysis, where the distance between line features is measured to calculate shoreline change, the comparison of the vegetation areas is not dependant on the position of the island polygons and therefore only requires images to be scaled correctly to calculate and compare areas. As such we only consider the pixel and digitizing errors in the uncertainty of the vegetation polygons, which range from 1.36 m to 2.21 m. In the case of the 1896 map sheets we use a mapping error of +/- 2.25 m. We conservatively estimate the uncertainty of island areas by buffering the island polygon by the associated uncertainty value of the vegetation line.

Table DR1. Sources of positional uncertainty of the edge of vegetation line.

	Map/Imagery Date					
	1897	**1943**	**1971**	**1984**	**2005**	**2013**
Pixel Size (m)		0.4	0.6	0.5	0.6	0.5
Rectification (m)		0.44 - 0.88	0.41 - 2.02	0.69 - 0.97	0.87	0
Interpretation (m)		2.17	2.12	2.12	1.27	1.27
Total Shoreline Error (m)	2.25	2.25 - 2.38	2.24 - 2.99	2.28 - 2.38	1.65	1.36

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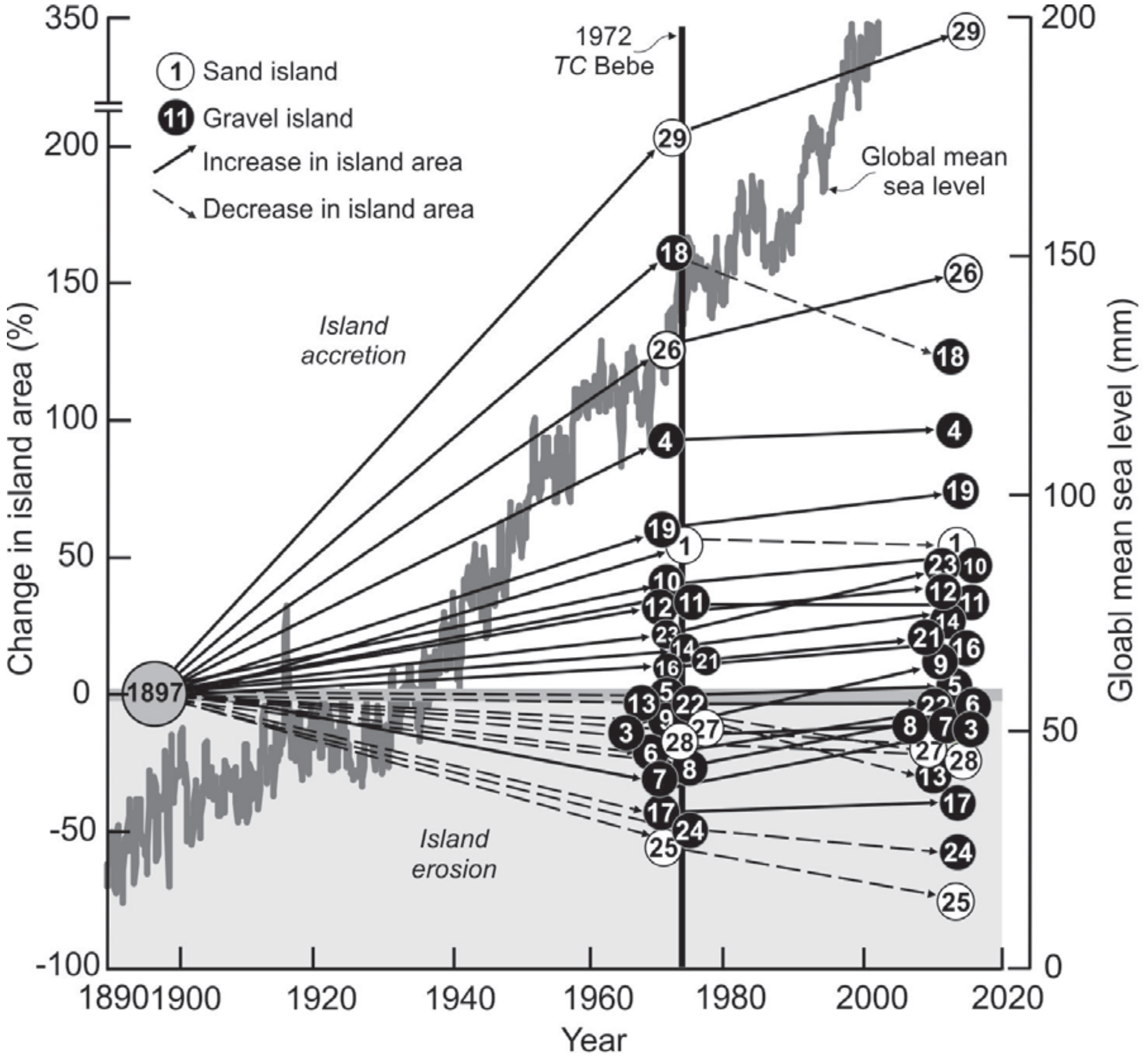
Table DR2. Funafuti reef island area calculations and changes in island area 1897-2013.

Isld. No.	Island Name	Island Areas						Change in Island Area						Island Core	Island Footprint	DSAS	
		1897[a] (ha)	1943[b] (ha)	1971[b] (ha)	1984[b] (ha)	2005[c] (ha)	2013[c] (ha)	1897 – 2013 (ha)	1897 – 2013 (%)	1897 – 1971 (ha)	1897 – 1971 (%)	1971 – 2013 (ha)	1971 – 2013 (%)	(ha)	(ha)	SCE (m)	NSM (m)
1	Fualefeke/Paava	5.24	7.77	8.31	8.53	8.18	7.79	2.55	48.8	3.07	58.5	-0.51	-6.16	5.4[1]	11.2	31.1	0.1
3	Mulitefala	2.73	-	2.26	2.45	2.40	2.44	-0.29	-10.6	-0.47	-17.3	0.18	8.12	1.9[3]	3.0	16.8	2.7
4	Amatuku	2.91	-	5.60	6.00	5.82	5.71	2.80	96.3	2.69	92.6	0.11	1.94	5.4[3]	6.4	6.2	-1.3
5	Fogafale	152.60	-	152.00	-	154.15	156.58	3.98	2.6	-0.60	-0.4	4.58	3.01	145.9[3]	179.4	5.7	1.2
6	Fatato	5.64	-	4.44	4.79	5.37	5.40	-0.24	-4.3	-1.20	-21.4	0.96	21.74	4.3[1]	5.8	7.2	4.7
7	Funagogo	12.60	-	9.00	10.94	10.90	11.04	-1.56	-12.4	-3.60	-28.5	2.03	22.57	7.5[1]	12.8	22.6	8.9
8	Funamanu	4.14	-	3.06	2.93	4.05	3.85	-0.29	-6.9	-1.08	-26.0	0.79	25.79	2.7[3]	4.3	11.1	4.7
9	Falefatu	3.21	-	2.90	2.77	3.49	3.58	0.37	11.6	-0.31	-9.6	0.68	23.45	2.3[3]	4.0	10.5	4.2
10	Mateiko	2.78	3.57	3.86	4.04	4.26	4.10	1.32	47.5	1.08	38.7	0.24	6.34	3.4[2]	4.6	7.5	3.2
11	Luamotu	1.24	1.71	1.67	1.61	1.70	1.67	0.43	35.2	0.43	35.0	0.00	0.08	1.3[2]	2.1	9.6	-0.4
12	Funafala	16.31	21.29	21.99	22.31	22.74	22.53	6.22	38.1	5.68	34.8	0.54	2.47	20.4[2]	24.0	6.5	2.9
13	Tefota	0.18	-	0.17	0.15	0.15	0.14	-0.04	-21.7	-0.01	-3.6	-0.03	-18.82	0.1[3]	0.2	-	-
14	Telele/Motusanapa	7.07	-	8.35	8.63	9.22	8.91	1.83	25.9	1.28	18.1	0.56	6.65	7.3[3]	10.2	9.9	2.4
16	Motuloa	3.43	3.59	3.80	3.58	4.76	4.02	0.59	17.0	0.36	10.5	0.22	5.88	2.9[2]	5.5	12.2	0.4
17	Nukusavalivali	0.77	0.43	0.43	0.48	0.46	0.47	-0.30	-38.4	-0.34	-44.4	0.05	10.76	0.2[2]	0.7	-	-
18	Motugie	0.07	0.16	0.19	0.16	0.16	0.16	0.09	121.5	0.12	160.6	-0.03	-15.00	0.1[2]	0.2	-	-
19	Avalau/Teafuafou	6.96	10.21	11.03	11.75	11.87	12.09	5.13	73.7	4.06	58.4	1.07	9.69	9.8[2]	13.0	14.9	7.6
21	Tegasu	0.52	0.60	0.59	0.68	0.62	0.63	0.11	20.5	0.07	13.5	0.04	6.13	0.5[2]	0.8	10.1	1.3
22	Tutaga	1.62	1.38	1.57	1.54	1.57	1.53	-0.09	-5.7	-0.05	-2.9	-0.05	-2.89	1.3[2]	1.7	7.6	3.2
23	Falaoigo	0.94	-	1.15	1.23	1.33	1.36	0.42	44.5	0.21	21.9	0.21	18.55	1.1[3]	1.4	7.4	4.4
24	Tefala	1.49	-	0.78	-	0.77	0.63	-0.86	-57.7	-0.71	-47.5	-0.15	-19.39	0.5[3]	0.9	13.6	-4.4
25	Fuagea	3.41	-	1.63	-	1.14	0.89	-2.53	-74.0	-1.78	-52.3	-0.74	-45.52	0.9[1]	1.6	14.5	-14.1
26	Fuafatu	1.33	2.73	3.02	-	3.32	3.38	2.04	153.3	1.69	126.6	0.36	11.78	2.6[2]	3.5	9.6	6.2
27	Fualopa	2.77	-	2.44	-	2.20	2.18	-0.59	-21.3	-0.33	-12.0	-0.26	-10.59	2.0[1]	2.5	6.7	-3.4
28	Tepuka	12.79	10.10	10.71	10.67	10.09	9.81	-2.97	-23.2	-2.08	-16.2	-0.89	-8.35	7.0[1]	13.9	60.5	-0.6
29	Teafualiku	0.07	0.26	0.22	0.30	0.23	0.31	0.24	342.9	0.15	214.3	0.09	40.91	0.1[2]	0.4	10.6	2.5
	Total/Net	**252.8**	**63.8**	**261.2**	**105.6**	**270.9**	**271.2**							-	-	-	-

Island area derived from 1897 geological maps[a], vertical aerial photography[b] and satellite imagery[c]. DSAS results: SCE = shoreline change envelope, NSM = net shoreline movement. Source data for core estimates are [1]=1897, [2]=1943, [3]=1971.



1=Fualefeke/Paava, 3=Mulitefala, 4=Amatuku, 5=Fogafale, 6=Fatato, 7=Funagogo, 8=Funamanu
9=Falefatu, 10=Mateiko, 11=Luamotu, 12=Funafala, 13=Tefota, 14=Telele/Motusanapa, 16=Motuloa
17=Nukusavalivali, 18=Motugie, 19=Avalau/Teafuafou, 21=Tegasu, 22=Tutaga, 23=Falaoigo
24=Tefala, 25=Fuagea, 26=Fuafatu, 27=Fualopa, 28=Tepuka, 29=Teafualiku

Figure DR3. Changes in island area, Funafuti atoll 1897-2013. Progressive changes in island area between 1897-1971 and 1971-2013. Numbers refer to islands, listed in Table DR1. Note: direction of arrows denotes erosion and accretion between time periods. Global mean sea level also presented from Church and White (2006). Note: labels for 2013 islands are shifted to avoid overlap.

Church, J.A., and White, N.J., 2006, A twentieth century acceleration in global sea level rise. Geophysical Research Letters, v. 33, L01602. doi:10.1029/2005GL024826.

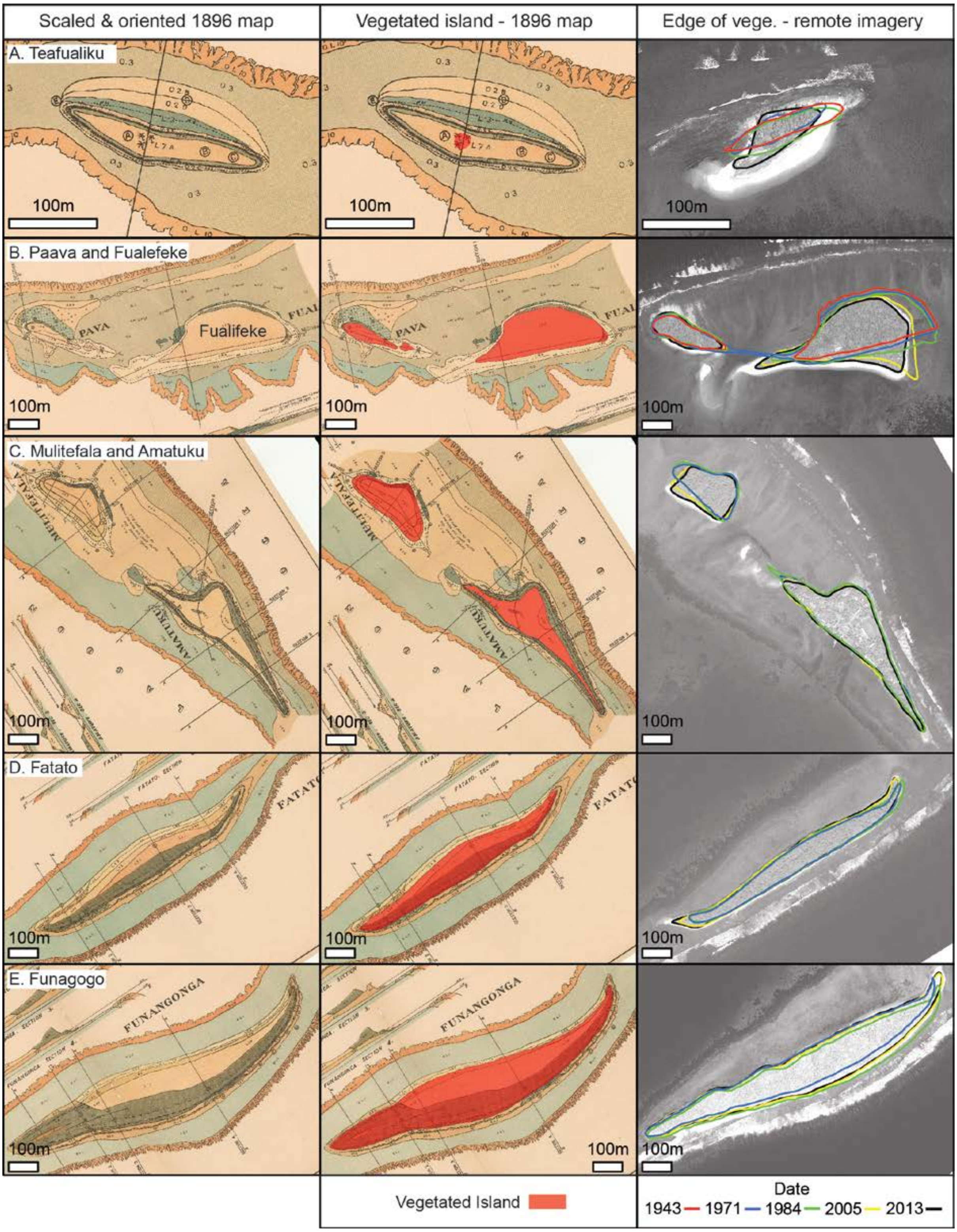
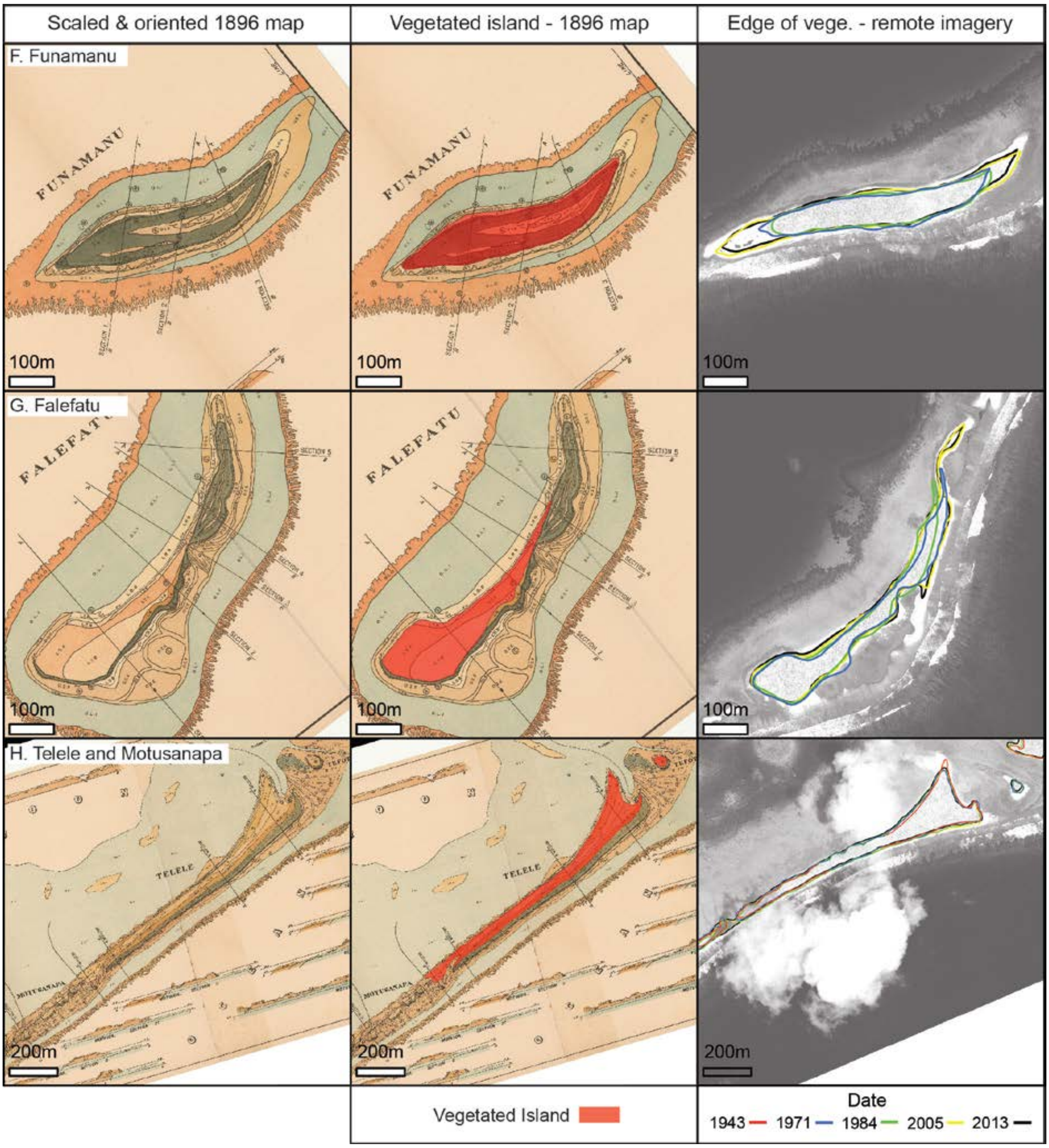


Figure DR4. Planform changes in islands of Funafuti atoll, 1897-2013. Location of islands shown in Figure DR1 and changes in island area contained in Table DR2.



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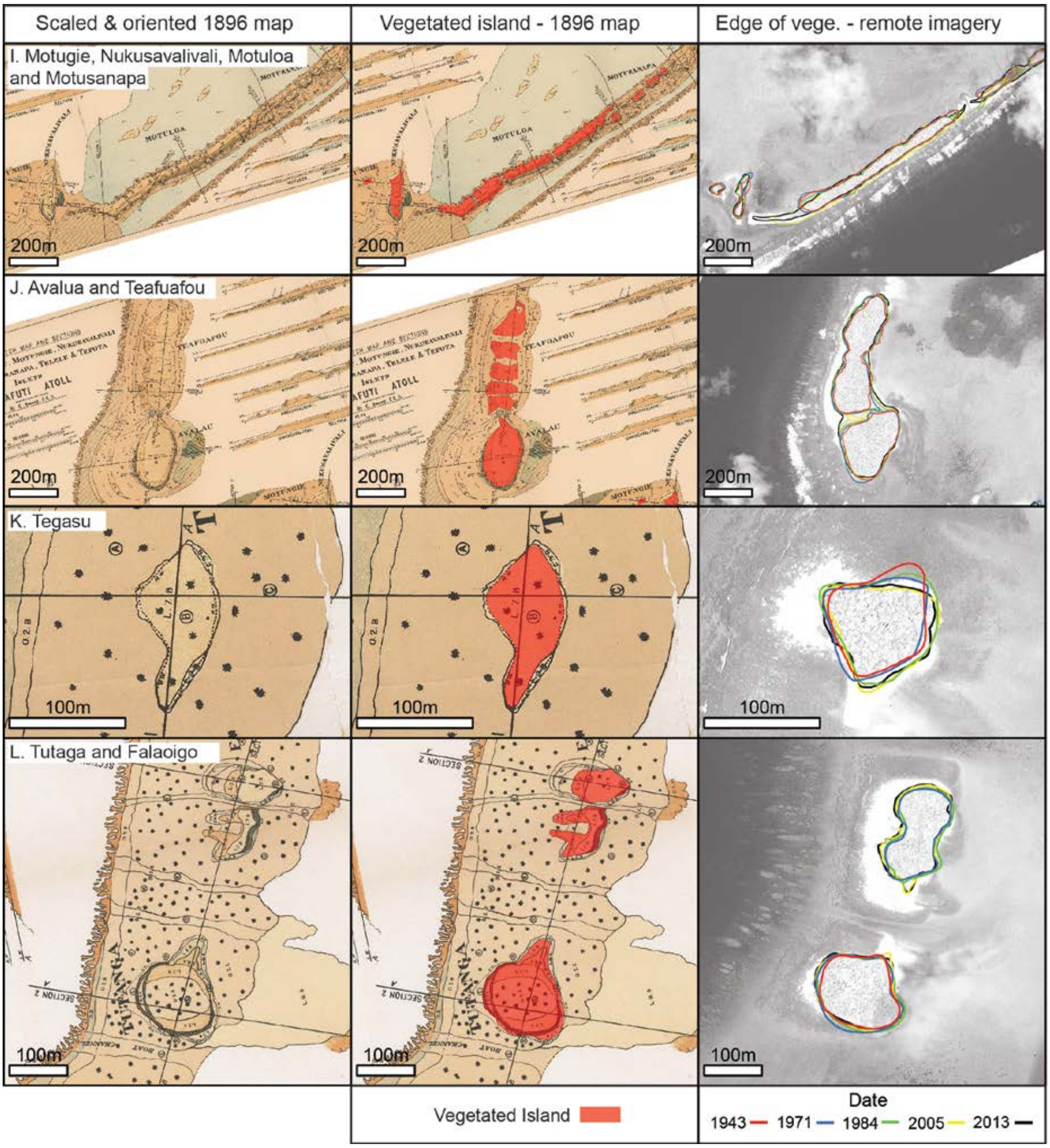

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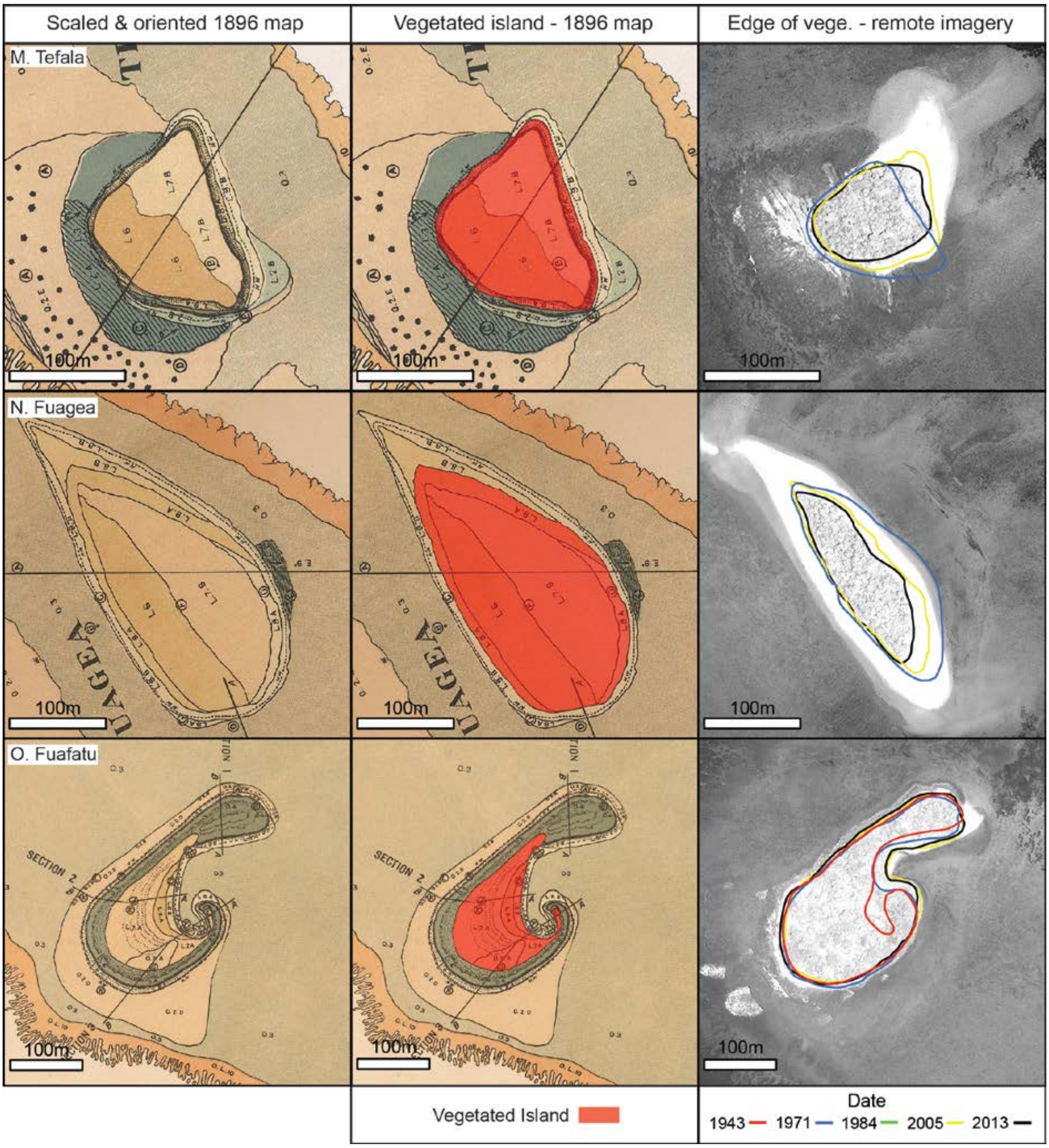

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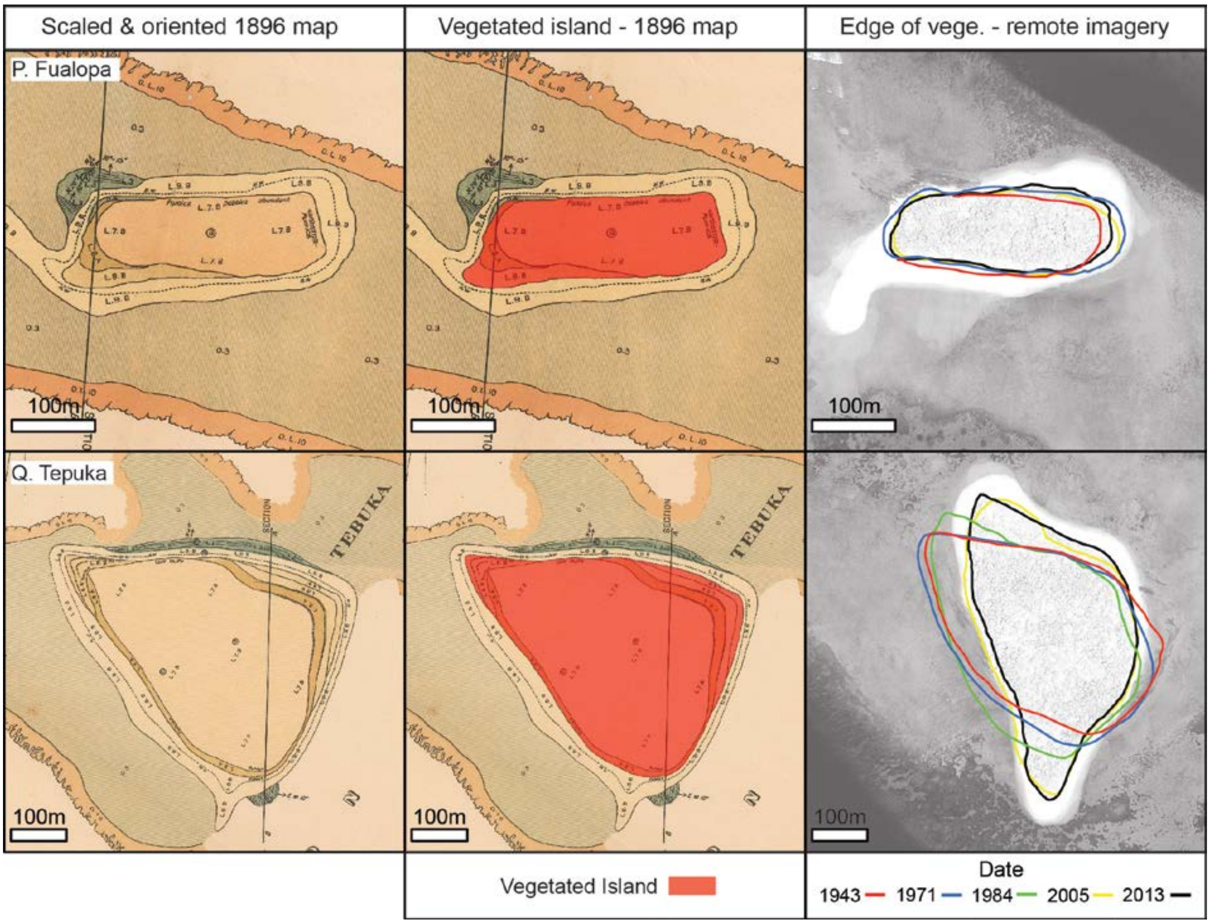

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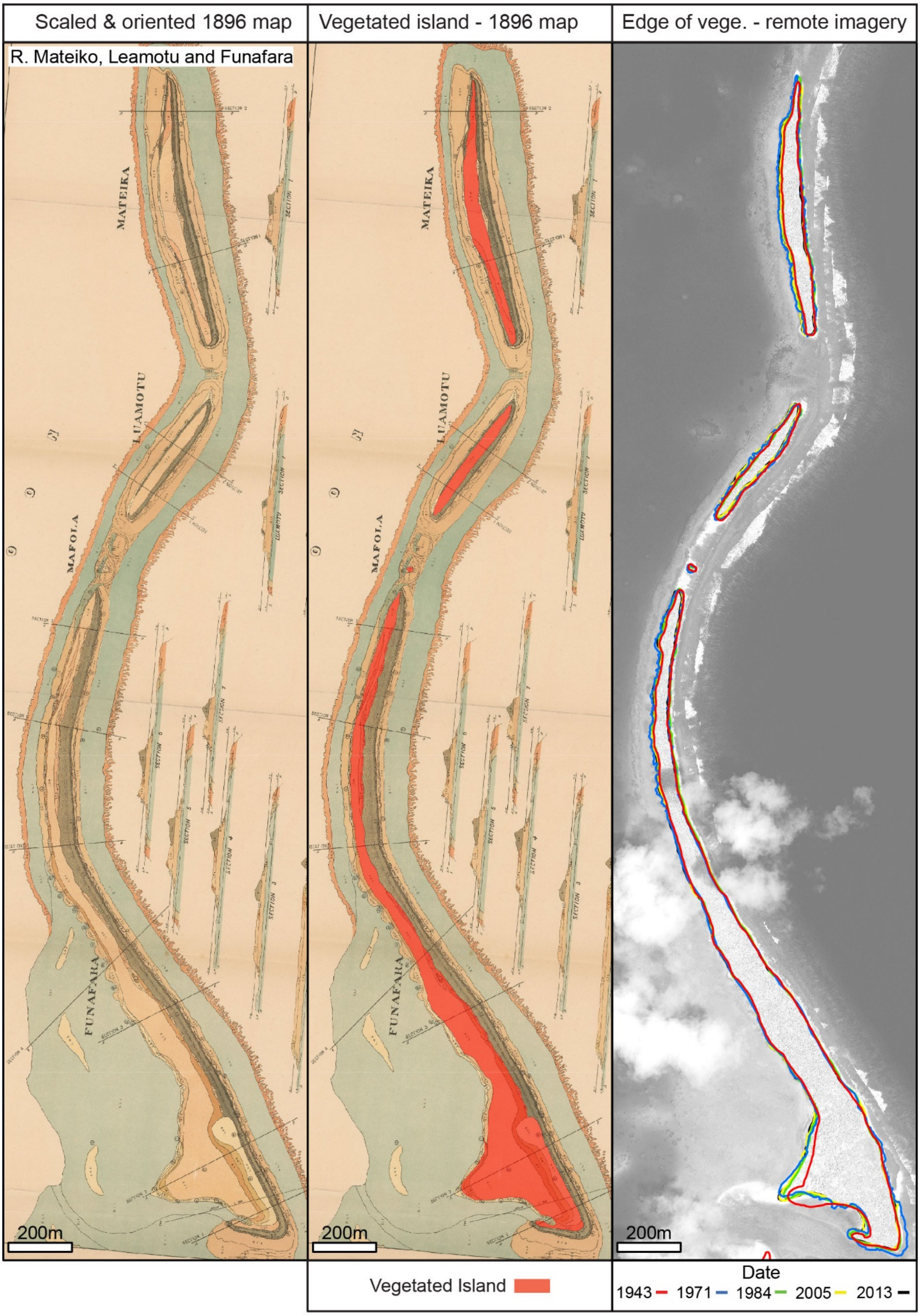

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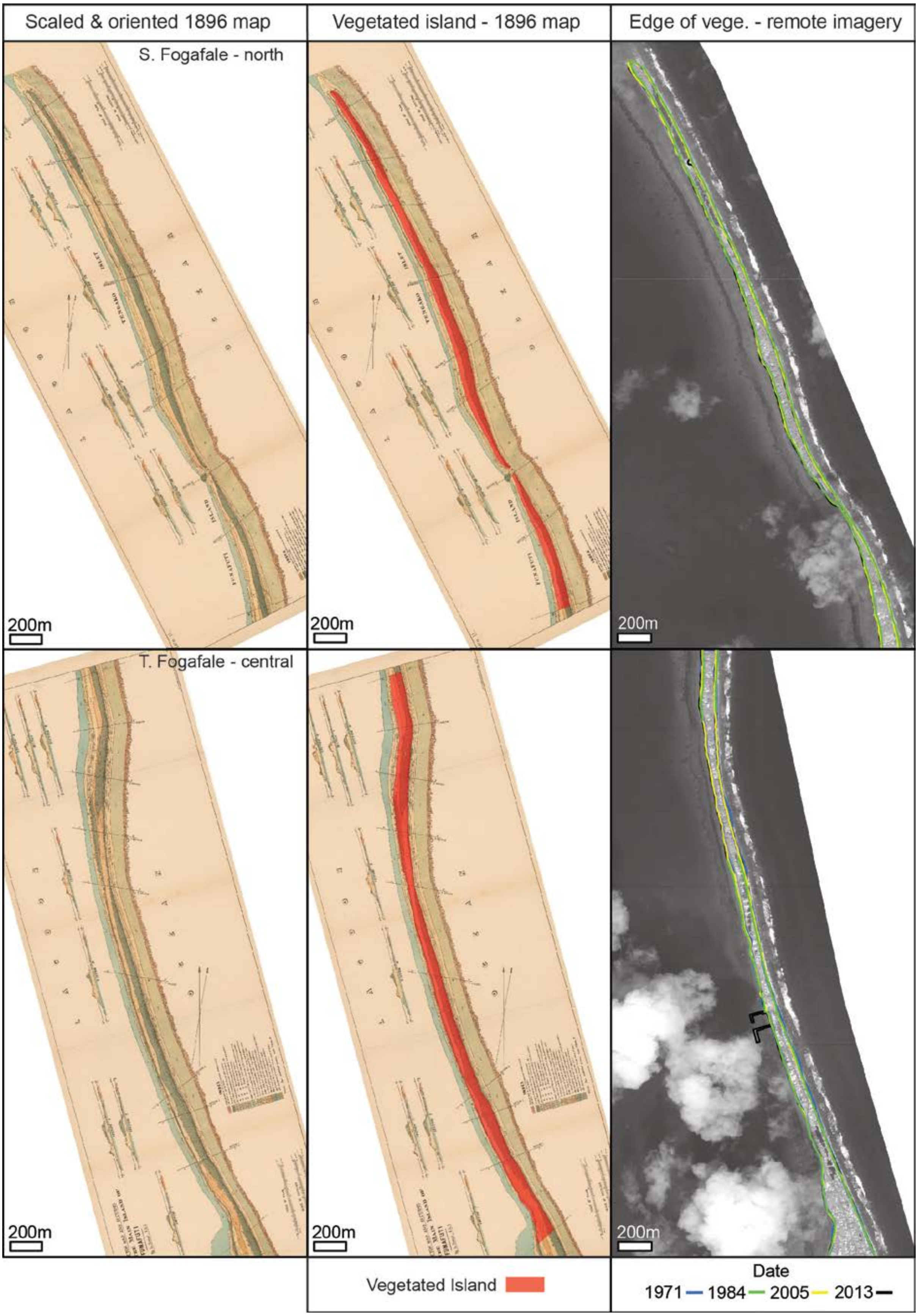

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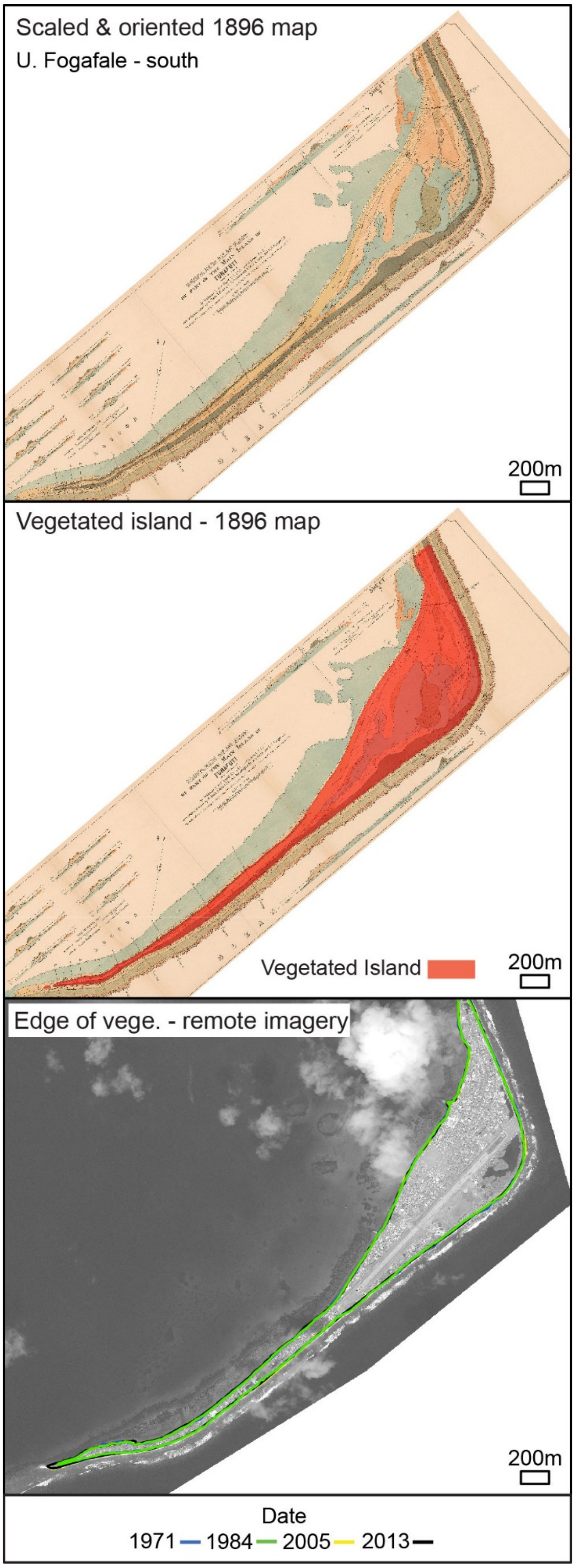

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