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SUPPLEMENTARY INFORMATION

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The potential of Indonesian mangrove forests for global climate change mitigation

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Methods

The description of the study site and sampling strategy described below will give the idea of the ecological spectrum and geographical coverage of the study. The assessment of Carbon stocks in all components is described in detail following the protocol widely used for global comparisons. Finally the variance of data collected is treated with appropriate statistical analysis before their averaged values are presented and narrated in the text.

Study sites, sampling strategy and design. C stocks in Cilacap, Tanjung Puting and Bunaken (13 plots) were quantified in 2010[(2)] and adapted for this study. Additional measurements (26 plots) in the Sembilang, Kubu Raya, Teminabuan, Bintuni, and Timika sites (see Fig. S1) were conducted in 2012 – 2013.

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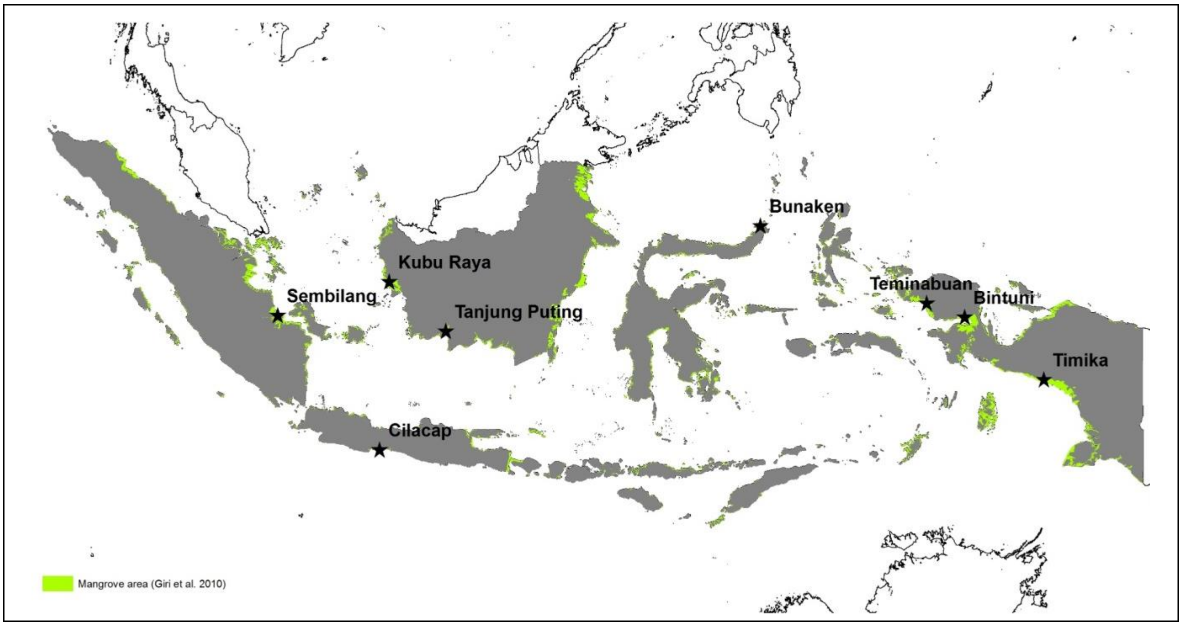

Figure S1. Study sites across the Indonesian Archipelago in which carbon stocks were sampled. These sites are in Sumatra (Sembilang, 6 plots), Java (Cilacap, 2 plots), Kalimantan (Kubu Raya, 7 plots and Tanjung Puting, 5 plots), Sulawesi (Bunaken, 6 plots), and West Papua (Teminabuan, 4 plots; Bintuni, 5 plots) and Papua (Timika, 4 plots).

Except in Cilacap, plots in all sites were relatively undisturbed. They are geographically scattered across the Indonesian archipelago and were randomly chosen. The variation of biophysical characteristics of each site is shown in Table S1.

Table S1. Biophysical characteristics of the selected sites

Site	Latitude	Longitude	Dominant species	Stature	Dominant hydro-geo-morphology	Number of plot and sampling area (ha)
Sembilang	02°04'28" S	104°28’09” E	*Rhizophora apiculate* *Bruguiera gymnorrhiza*	Mixed	Riverine	6 (3.0)
Kubu Raya	00°40'33" S	109°21’41” E	*Rhizophora apiculata*	Tall	Riverine	7 (3.5)
Tanjung Puting	02°51'30" S	111°42’02” E	*Rhizophora apiculata*	Tall	Riverine	5 (2.5)
Cilacap	07°43'25" S	108°57’29” E	*Sonneratia alba*	Short	Estuarine	2 (1.0)
Bintuni	02°10'12" S	133°32’09” E	*Bruguiera gymnorrhiza*	Tall	Estuarine	5 (2.5)
Teminabuan	01°37'24" S	131°48’35” E	*Bruguiera gymnorrhiza* *Avicennia spp.*	Mixed	Riverine Marine	4 (2.0)
Timika	04°51'41" S	136°47’18” E	*Rhizophora apiculata*	Tall	Riverine	4 (2.0)
Bunaken	01°17'17" N	124°30’37” E	*Rhizophora mucronata*	Short	Marine	6 (3.0)

The sample design and data analysis at all 39 sites followed the widely used protocols[31]. Carbon stocks of each site was accomplished through measurements of all pools in 6 plots established along transects at 25 m intervals.

Biomass carbon. Biomass of mangrove trees was determined by measuring their diameter at 130 cm aboveground or for *Rhizophora spp* around 30 cm above the highest stilt root. We recorded trees with diameters > 5 cm inside a 7 m radius circular plot and saplings <5 cm in diameter within a 2 m radius circular nested plot. We employed both species-specific and general allometric equations from published studies to calculate aboveground tree biomass and belowground root biomass (Table S4). To obtain biomass carbon stock per unit area (Mg C ha^{-1}), we multiplied biomass by commonly used C proportions of 0.47 and 0.39 for aboveground trees and belowground roots biomass per unit area, respectively.

Dead wood carbon. Dead and downed wood including stem, branch and prop root debris lying on the forest floor was measured by using the planar intercept technique. We classified dead and downed wood into four classes, including fine (<0.6 cm), small (0.6 – 2.5 cm), medium (2.5 – 7.5 cm), and large (>7.5 cm) sizes for sound or rotten dead wood. Dead downed wood biomass carbon stock was obtained by multiplying biomass (kg) with C content correction value of 0.5.

Soil carbon. Soil cores were collected at the center of each sub plot by using stainless steel 5.5 cm diameter open-faced auger. In each core, five sub samples of 96 cm^3 each were collected from depth intervals 0 – 15, 15 – 30, 30 – 50, 50 – 100 and 100 – 300 cm. The samples were analyzed for bulk density, and C and N concentration. The C and N were determined via the dry combustion method using a *Vario Max* CNS Analyzer at Soil Biotechnology Laboratory, Bogor Agricultural University. Soil C density was obtained by multiplying soil bulk density by soil C concentration. Soil C pools at each sampled depth was obtained by multiplying C density with the depth interval.

Ecosystem C stocks and C emissions. The ecosystem C stocks were the sum of C pools in all components. To scale stand-level estimates to entirety of the Archipelago, we multiplied the mean ecosystem C stocks by the areal extent of Indonesia's mangroves. In order to represent uncertainty in C stocks used the 5^{th} percentiles representing the lower end of our data set and 95^{th} percentiles representing the upper end.

C emissions were estimated using the stock change approach[14], where emissions were calculated as the difference in carbon stocks between intact and degraded sites. Intact sites were the mean carbon stocks reported in this study while degraded stocks were assumed to be 11% as reported by Kauffman *et al*.[7] as the lower threshold.

Statistical Analysis. All analyses were conducted using the Statistical Package for the Social Sciences (SPSS) *Statistics 19.0 for Windows 41.* We tested for differences in the variance of soil properties (dependent variables) with depth (independent variable). We used a nonparametric Kruskal – Wallis test for significance. If significant, a Mann – Whitney 2 independent samples test[32] was used to determine significance among sites.

This Supplementary Information also includes additional Supplementary Tables. They contain large size of dataset and are fully referenced in the text. These Tables are:

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Table S2 shows the soil properties required to calculate C stocks in soil compartment in each plot for all sites sampled. Aboveground tree biomass and woody debris carbon, and belowground root and soil carbon of the same plots were added to obtained ecosystem C stocks. The calculated C stocks in each compartment and in the ecosystem are discussed in terms of their mean within sites and their lowest, highest and grand mean across sites. Furthermore, C stocks from individual plots are treated as data population of Indonesian mangroves, from which, uncertainties of the estimates may be reduced by propagating the errors using the percentiles functions.

Table S3 shows the variability of soil properties (bulk density, C content and C density) with depth in all 39 plots studied. The statistical variance of dependent variables with depth is performed for each site.

Table S4 shows the allometric equations for above and belowground biomass of major species found in most sites including *Avicennia spp., Bruguiera spp., Rhizophora spp., Sonneratia alba,* and *Xylocarpus granatum.* The use of species allometric equation was to reduced uncertainties which are higher when general allometric equation was used.

Table S2. Soil properties and the C mass pools of aboveground and belowground ecosystem pools in all sites

Site and Coordinate	Plot	Soil Properties				C stocks (Mg C ha^{-1})				
		Mean depth (cm)	BD (g cm^{-3})	C (%)	C density (mg C cm^{-3})	Soil	Tree	Root	Woody debris	Total Ecosystem
Sembilang 02°04'28" S 104°28'09" E	Sembilang 1	176	0.75	5.93	42.99	778.3	383.5	33.8	2.4	1198.0
	Sembilang 2	213	0.48	12.02	56.05	1223.9	279.9	27.7	10.9	1542.4
	Sembilang 3	186	0.39	13.54	51.63	936.7	418.0	30.2	9.4	1394.3
	Sembilang 4	187	0.66	8.84	55.95	1074.2	255.8	29.9	16.9	1376.7
	Sembilang 5	157	0.65	9.06	58.10	914.8	219.6	24.2	10.3	1168.9
	Sembilang 6	182	0.69	7.18	48.68	948.8	245.9	21.6	18.1	1234.5
	Site mean	**183**	**0.60**	**9.43**	**52.24**	**979.5**	**300.5**	**27.9**	**11.3**	**1319.1**
Cilacap 07°43'25" S 108°57'29" E	Cilacap 1	142	0.55	5.73	31.45	430.0	1.9	0.2	12.3	444.4
	Cilacap 2	281	0.44	5.54	23.99	713.2	12.0	4.8	11.3	741.2
	Site mean	**211**	**0.50**	**5.64**	**27.72**	**571.6**	**6.9**	**2.5**	**11.8**	**592.8**
Kubu Raya 00°40'33" S 109°21'41" E	Kubu Raya 1	137	0.39	14.19	50.57	657.4	152.0	9.4	6.7	825.5
	Kubu Raya 2	138	0.52	8.97	45.08	622.5	113.6	18.2	15.6	769.8
	Kubu Raya 3	152	0.63	7.58	44.24	684.1	68.4	12.6	4.6	769.8
	Kubu Raya 4	138	0.62	7.92	47.27	643.9	38.0	5.1	62.6	749.7
	Kubu Raya 5	124	0.75	5.50	38.14	495.5	133.9	15.0	19.3	663.7
	Kubu Raya 6	139	0.71	7.30	47.10	642.4	189.3	15.9	38.6	886.2
	Kubu Raya 7	127	0.65	7.36	46.39	600.3	248.7	23.7	22.2	894.9
	Site mean	**136**	**0.61**	**8.40**	**45.54**	**620.9**	**134.8**	**14.3**	**24.2**	**794.2**
Tanjung Puting 02°51'30" S 111°42'02" E	Tanjung Puting 1	300	0.33	8.63	27.93	943.5	70.7	10.4	11.2	1035.7
	Tanjung Puting 2	300	0.33	7.09	23.24	813.9	169.4	10.9	9.0	1003.2
	Tanjung Puting 3	300	0.34	10.20	33.38	1049.0	207.9	21.2	17.3	1295.4
	Tanjung Puting 4	300	0.27	11.84	31.90	1234.5	86.5	23.5	19.0	1363.5
	Tanjung Puting 5	300	0.35	10.93	37.86	1255.0	170.0	40.6	36.7	1502.3
	Site mean	**300**	**0.32**	**9.74**	**30.86**	**1059.2**	**140.9**	**21.3**	**18.6**	**1240.0**
Bunaken 01°17'17" N 124°30'37" E	Bunaken 1	46	0.28	21.72	60.06	283.9	33.2	5.9	85.3	408.3
	Bunaken 2	97	0.30	19.28	55.54	560.3	48.8	4.2	24.0	637.2
	Bunaken 3	85	0.62	12.20	73.37	629.4	60.0	29.8	41.1	760.3
	Bunaken 4	300	0.40	18.14	72.20	2063.7	109.6	12.5	21.9	2207.7
	Bunaken 5	98	0.55	13.86	72.52	682.3	58.5	26.7	31.8	799.3
	Bunaken 6	78	0.77	8.55	65.22	650.3	105.3	10.2	51.9	817.8
	Site mean	**117**	**0.49**	**15.63**	**66.49**	**811.6**	**69.2**	**14.9**	**42.7**	**938.4**

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Teminabuan 01°37'24" S 131°48'35" E	Teminabuan 1	119	0.41	15.16	57.93	706.8	292.1	60.0	30.7	1089.7
	Teminabuan 2	141	0.50	9.63	47.24	687.8	313.1	42.8	15.5	1059.2
	Teminabuan 3	127	0.76	3.57	22.61	282.3	110.8	26.2	5.6	425.0
	Teminabuan 4	229	0.44	11.36	43.76	965.1	69.1	17.6	18.1	1070.0
	Site mean	**154**	**0.53**	**9.93**	**42.88**	**660.5**	**196.3**	**36.7**	**17.5**	**910.9**
Bintuni 02°10'12" S 133°32'09" E	Bintuni 1	215	0.54	9.15	47.65	1064.7	317.3	25.3	5.6	1412.9
	Bintuni 2	286	0.66	5.42	34.14	920.2	436.1	73.6	10.4	1440.3
	Bintuni 3	264	0.62	8.05	48.95	1324.6	306.8	35.3	15.8	1682.5
	Bintuni 4	290	0.61	7.36	40.03	894.8	279.4	51.6	28.5	1254.2
	Bintuni 5	269	0.72	6.10	39.47	869.7	278.6	32.2	13.7	1194.3
	Site mean	**265**	**0.63**	**7.22**	**42.05**	**1014.8**	**323.6**	**43.6**	**14.8**	**1396.9**
Timika 04°51'41" S 136°47'18" E	Timika 1	170	0.46	13.56	56.67	922.6	146.2	28.9	17.8	1115.6
	Timika 2	156	0.71	7.24	49.05	756.3	266.2	42.1	32.7	1097.2
	Timika 3	285	0.60	8.25	43.94	1157.6	147.5	8.9	20.0	1333.9
	Timika 4	227	0.46	11.56	47.69	1023.8	460.3	28.7	41.0	1553.9
	Site mean	**209**	**0.56**	**10.15**	**49.34**	**965.1**	**255.1**	**27.2**	**27.9**	**1275.2**
Grand mean		**191**	**0.54**	**9.89**	**46.67**	**848.9**	**187.3**	**24.1**	**22.2**	**1082.6**
Percentage (%)						**78.4**	**17.3**	**2.2**	**2.1**	**100**

Table S3. Mean bulk density, C content and C density partitioned by depth and site. Numbers are mean ± one standard error. Different superscripted letters denote a significant difference between soil depths (p value = 0.01).

Bulk Density (g cm^{-3})

Depth (cm)	Sembilang	Cilacap	Kubu Raya	Tanjung Puting	Bunaken	Teminabuan	Bintuni	Timika	Mean
	X±SE	X±SE	X±SE	X±SE	X±SE	X±SE	X±SE	X±SE	X±SE
0-15	0.57±0.02^{a}	0.48±0.03^{a}	0.59±0.03^{a}	0.28±0.01^{a}	0.49±0.04^{a}	0.41±0.02^{a}	0.61±0.03^{a}	0.50±0.04^{a}	0.50±0.01^{a}
15-30	0.57±0.03^{a}	0.47±0.03^{a}	0.57±0.03^{a}	0.30±0.01^{a}	0.48±0.04^{a}	0.50±0.04^{a}	0.59±0.02^{a}	0.48±0.04^{a}	0.50±0.01^{a}
30-50	0.62±0.03^{a}	0.50±0.02^{a}	0.57±0.02^{a}	0.29±0.01^{a}	0.49±0.04^{a}	0.57±0.05^{ab}	0.57±0.02^{a}	0.52±0.03^{a}	0.52±0.01^{a}
50-100	0.61±0.03^{a}	0.50±0.04^{a}	0.59±0.03^{a}	0.30±0.01^{a}	0.50±0.04^{a}	0.56±0.06^{ab}	0.63±0.03^{a}	0.57±0.04^{ab}	0.54±0.01^{ab}
100-300	0.66±0.02^{ab}	0.53±0.02^{a}	0.73±0.02^{b}	0.45±0.01^{b}	0.43±0.03^{a}	0.62±0.05^{ab}	0.76±0.03^{b}	0.73±0.04^{c}	0.65±0.01^{c}
Sig. diff.	Ns	ns	**	**	Ns	**	**	**	**

C content (%)

Depth (cm)	Sembilang	Cilacap	Kubu Raya	Tanjung Puting	Bunaken	Teminabuan	Bintuni	Timika	Mean
	X±SE	X±SE	X±SE	X±SE	X±SE	X±SE	X±SE	X±SE	X±SE
0-15	9.72±0.56^{a}	5.46±0.30^{a}	9.18±0.79^{a}	9.98±0.38^{a}	16.05±0.98^{a}	11.20±1.26^{a}	7.49±0.56^{a}	11.39±0.97^{a}	10.45±0.34^{a}
15-30	9.70±0.67^{a}	5.80±0.24^{a}	8.80±0.68^{a}	9.65±0.41^{a}	16.00±0.96^{a}	11.07±1.37^{a}	8.63±0.56^{a}	12.12±1.00^{a}	10.55±0.34^{a}
30-50	9.16±0.65^{a}	5.89±0.34^{a}	9.14±0.62^{a}	10.06±0.37^{a}	14.88±0.85^{a}	10.87±1.83^{a}	7.70±0.48^{a}	10.65±0.85^{a}	10.04±0.33^{a}
50-100	9.92±0.69^{a}	5.67±0.23^{a}	8.37±0.50^{a}	10.42±0.46^{a}	14.94±0.89^{a}	9.51±1.14^{a}	6.94±0.48^{a}	10.23±0.79^{a}	9.69±0.29^{a}
100-300	8.63±0.40^{a}	5.01±0.25^{a}	6.54±0.22^{b}	8.58±0.36^{ab}	15.72±1.51^{a}	7.00±0.81^{ab}	5.32±0.45^{b}	6.37±0.47^{b}	7.30±0.22^{b}
Sig. diff.	Ns	ns	**	*	Ns	ns	**	**	**

C density (mg C cm^{-3})

Depth (cm)	Sembilang	Cilacap	Kubu Raya	Tanjung Puting	Bunaken	Teminabuan	Bintuni	Timika	Mean
	X±SE	X±SE	X±SE	X±SE	X±SE	X±SE	X±SE	X±SE	X±SE
0-15	51.47±1.67^{a}	26.18±2.11^{a}	45.00±1.95^{a}	28.02±1.29^{a}	66.79±3.18^{a}	41.92±3.98^{a}	42.28±2.14^{a}	49.34±1.86^{a}	45.99±1.15^{a}
15-30	49.51±1.59^{a}	26.99±1.80^{a}	44.05±1.73^{a}	28.23±1.57^{a}	67.27±2.48^{a}	45.68±3.74^{a}	47.76±1.88^{a}	51.31±2.26^{a}	46.95±1.08^{ab}
30-50	50.59±2.21^{a}	29.01±1.68^{a}	47.22±1.81^{a}	28.72±1.43^{a}	65.72±2.36^{a}	46.00±4.41^{a}	41.87±1.69^{ab}	50.65±1.98^{a}	46.49±1.08^{a}
50-100	54.89±2.58^{a}	27.62±1.53^{a}	45.27±1.25^{a}	31.27±1.94^{a}	68.06±3.40^{a}	42.63±4.87^{a}	40.90±2.12^{ab}	52.97±2.62^{a}	46.79±1.20^{a}
100-300	54.73±1.95^{a}	26.17±0.83^{a}	46.19±1.14^{a}	38.06±1.69^{b}	65.63±4.49^{a}	38.17±4.88^{ab}	37.44±2.36^{ab}	42.43±1.51^{b}	43.65±1.03^{ab}
Sig. diff.	Ns	ns	ns	**	Ns	ns	**	**	ns

Significant difference denoted as: ** = highly significant * = significant, ns = non-significant.

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Table S4. Allometric equations used to determine tree mass and carbon pools of the major mangroves species encountered in the study areas

Species	AGB / Tree (kg)	Reference	BGB / Root (kg)	Reference
Avicennia marina; *Avicennia alba*	$AGB = 0.308*D^{2.11}$	33	$BGB = 1.28*DBH^{1.17}$	33
Bruguiera gymnorrhiza; *Bruguiera sexangula;* *Bruguiera cylindrica*	Wood volume (Wv): $Wv = 0.0000754*(DBH^{2.5})$ Leaf biomass (Lb): $Lb = 10^{(-1.1679+(1.4914*(LOG(DBH))))}$ Wood biomass (Wb): $Wb = Wv*\rho*1000$ AGB = Lb + Wb	34	$BGB = 0.0188*DBH^{2}*(DBH/(0.025DBH + 0.583))^{0.909}$	35
Bruguiera parviflora	$AGB = 0.168*DBH^{2.42}$	36	$BGB = 0.0188*DBH^{2}*(DBH/(0.025DBH + 0.583))^{0.909}$	35
Rhizophora spp.	Wood volume (Wv): $Wv = 0.0000695*DBH^{2.64}$ Leaf biomass (Lb): $Lb = 10^{(-1.8571+(2.1072*(LOG(DBH))))}$ Wood biomass (Wb): $Wb = Wv*\rho*1000$ Prop root biomass (PRb): DBH≤5 cm PRb = Wb*0.101 DBH>5.0≤ 10 cm PRb = Wb*0.204 DBH>10≤ 15.0 cm PRb = Wb*0.356 DBH>15≤ 20.0 cm PRb = Wb*0.273 DBH>20 cm PRb = Wb*0.210 AGB = Lb + Wb + PRb	34	$BGB = 0.00698*DBH^{2.61}$	37
Sonneratia alba	Wood volume (Wv): $Wv = 0.0003841*DBH^{2.10}$ Leaf biomass (Lb): $Lb = 10^{(-1.1679+(1.4914*(LOG(DBH))))}$ Wood biomass (Wb): $Wm = Wv*\rho*1000$ AGB = Lb + Wb	34	$BGB = 0.199*\rho^{0.899}*DBH^{2.22}$	38
Xylocarpus granatum	$AGB = 0.0823*DBH^{2.59}$	36	$BGB = 0.199*\rho^{0.899}*DBH^{2.22}$	38
Other species	$AGB = 0.251*\rho*DBH^{2.46}$	38	$BGB = 0.199*\rho^{0.899}*DBH^{2.22}$	38

Note: AGB = Aboveground biomass (kg); BGB = Belowground biomass (kg); DBH = Diameter at breast height (cm); ρ = wood density (g cm^{-3})

Table S5. Indonesian active shrimp pond area (ha) and distribution that leveled off at around 0.65 Mha since 2006[9]

	2006	2007	2008	2009	2010	2011	2012
Sumatera	130,589	133,021	126,137	144,374	128,044	124,939	111,470
Java	165,854	170,089	157,976	156,049	173,216	173,139	176,316
Bali - Nusa Tenggara	8,927	8,769	8,312	8,918	8,515	8,935	8,346
Kalimantan	144,254	107,574	197,787	213,089	211,323	287,553	208,112
Sulawesi	144,412	134,130	125,875	145,272	152,843	153,677	151,899
Maluku - Papua	2,999	2,343	2,166	2,037	8,917	978	1,204
Total	597,035	555,926	618,253	669,739	682,858	749,221	657,347

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