Cite as: J. L. Sabo *et al.*, *Science*
10.1126/science.aav9887 (2019).

Response to Comment on "Designing river flows to improve food security futures in the Lower Mekong Basin"

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Williams *et al.* claim that the data used in Sabo *et al.* were improperly scaled to account for fishing effort, thereby invalidating the analysis. Here, we reanalyze the data rescaled per Williams *et al.* and following the methods in Sabo *et al.* Our original conclusions are robust to rescaling, thereby invalidating the assertion that our original analysis is invalid.

Williams *et al.* (*1*) claim that the monitoring data we used to design flows that maximize harvest in the Dai fishery of Cambodia's Tonle Sap River (*2*) were not properly scaled to account for both sampling and fishing effort, and hence the results are invalid. First, we note that our analysis was multifaceted, including historical analysis of the effects of dams on hydrologic variation, a historical analysis of the links between hydrology and harvest at the Dai fishery, and a forward-looking thought experiment about how dams could be managed to sustain or enhance harvest as they come online. Williams *et al.* address only the last two portions of the analysis. With regard to scaling of the monitoring data, Williams *et al.* contend that our analysis should have been performed following the methods of a technical report by Halls *et al.* (*3*). The implication is that, because monitoring inconsistencies and known biological variation were not accounted for, the entirety of the analysis is flawed.

We agree with Williams *et al.* that scaling of the Dai fishery monitoring data is an important consideration. However, it is impossible to say anything about the effect of scaling decisions on the results without performing the analysis presented in Sabo *et al.* (*2*) with the addition of scaling. Here, we present a reanalysis of Sabo *et al.* (*2*) using a scaling method that addresses the main considerations identified in Williams *et al.* This reanalysis demonstrates that the key results presented in (*2*) are robust.

The Tonle Sap Dai fishery consists of roughly 64 individual bagnets distributed among 14 "Dai rows" that are placed longitudinally in the Tonle Sap River. Catch at the Dais is not temporally or spatially homogeneous. Fish that are targeted by the Dai fishery migrate on a lunar cycle, with peak migration and peak catch typically about 6 days before the full moon. Downstream Dais should have lower catch per unit effort (CPUE) than upstream Dais as migrating fish are removed by the fishery upstream. Previous work has also used a classification system that identifies certain Dais as "high-yield" as a result of their position in the river. Finally, it is conceivable that fish abundance and catches would vary systematically across the course of a fishing season.

Catch at the Dai fishery has been monitored heterogeneously for a variety of reasons influenced by political conditions and local capacity. The Halls *et al.* method (*3*) attempts to scale the Dai monitoring data to correct for inconsistent spatial and temporal sampling in order to estimate absolute or total catch (kg) among two political districts in each fishing season. Thus, scaling is used to extrapolate from the subset (sample) to the total fishery yield over the full open season. Our analysis differs from this in two important ways: (i) We are interested in CPUE as an effort-independent metric of fish abundance. This involves fewer steps and assumptions than when estimating total catch as per Halls *et al.* (*3*). (ii) The subsequent multivariate autoregressive state space (MARSS) time-series analysis uses each Dai row as spatially explicit replicates, and thus we needed annual data by Dai row (n = 14). Therefore, we calculated a new average annual CPUE dataset that meets the constraints of our spatially replicated MARSS model and is adjusted for potential temporal biases due to migration timing.

This new approach considers the effect of lunar cycle but does not make any assumptions regarding productivity (high- versus low-yield classification of Dais) or the effect of period within the fishing season. Hence, we refer to the new dataset as the "lunar adjusted CPUE" dataset, and our former dataset presented in Sabo *et al.* (*2*)—catch summed across Dai rows within years, scaled by days of effort—as the "simple CPUE" dataset.

Survey data obtained from the Mekong River Commission included information on the single-day catch biomass for an individual Dai by species and identified whether a given sample occurred during the peak-migration period or low-migration period. That is, the data were previously scaled from catch per haul to catch per day by multiplying the average catch per haul by number of hauls, observed for the day of the survey. The Dai fishery operates continually 24 hours a day; thus, kg $\mathrm{Dai}^{-1}\,\mathrm{day}^{-1}$ is a standardized metric of CPUE. In scaling the data to average CPUE of all fish for the season, the first step was to sum the total daily catch for each species into total single daily fish catch with units of kg $\mathrm{Dai}^{-1}\,\mathrm{day}^{-1}$. Next, all samples from a Dai row (j) during each migration period (p) in a given season (i) were averaged irrespective of the month of the sample or whether the sampled Dai was categorized as high- or low-yield. The effect of migration period was accounted for by taking the peak- and low-migration CPUE within each Dai row and season and calculating a weighted average based on proportion of days in each season that are peak and low:

$$\text{average CPUE}_{i,j} = P_{p=\text{peak},i}\text{CPUE}_{p=\text{peak},i,j} + P_{p=\text{low},i}\text{CPUE}_{p=\text{low},i,j} \tag{1}$$

The proportion of fishing days that were peak-migration was determined on the basis of a lunar model (package *lunar* in R) that provides the moon phase for any location on Earth past and future. We used number of days when the moon phase was full in each season as the number of days of peak migration. This does not correspond to the same exact days of the peak migration, as this is typically 6 days prior to the full moon. Nonetheless, both the full-moon period and the peak-migration period last about a week, so we considered this a reasonable approximation of total number of days in a given season. Total fishing days was the number of days between 1 October and 31 March in each season (182 days; 183 days in leap years). The proportion of days that were peak-migration was roughly 25% of the fishing season. Because we are not scaling to total catch, it is not critical to know the exact number of peak-migration days, only the relative proportions. This method is a relatively unbiased way to estimate the effect of lunar migration that is evenly applied across years.

Plotting lunar adjusted CPUE across years by Dai row (Fig. 1) reveals the expected decline moving upstream (Dai 15) to downstream (Dai 2) mentioned by Williams *et al.* (*1*) that reflects the removal of fish by the fishery. The average annual lunar adjusted CPUE across Dai rows (Fig. 2) reflects substantial interannual variation. Annotated R code for the lunar adjusted CPUE calculation is provided via Figshare (*4*).

The correlation between lunar adjusted CPUE and the data used in Sabo *et al.* (*2*) (simple CPUE) is high. Spearman correlation coefficients (based on ranked data within each Dai row) between the lunar adjusted and simple CPUE datasets averaged 0.68 (range 0.40 to 0.94; SD = 0.15) across 14 possible time-series pairs (one per Dai row). As in Sabo *et al.* (*2*), we fitted a density-independent MARSS model using historical hydrology as covariates [high-level drivers: flood pulse extent (FPExt) and net annual anomaly (NAA)] and the new, lunar adjusted CPUE data as variates. The bootstrapped MARSS model coefficients preserved their sign (i.e., direction) from the original analysis and increased slightly in effect size, and the confidence intervals ($\alpha = 0.05$) continued not to overlap with zero (Table 1). Interestingly, the effects of the flood pulse (high flows) and the net annual anomaly (here, indicative of low flows) were both higher in magnitude, which suggests that these covariates may be identified as even more important with the lunar adjusted CPUE data. This variation and the FPExt and NAA covariate data were the key structural components of design flows in Sabo *et al.* (*2*). Hence, reconstructing the hypothetical future scenario presented in (*2*) with lunar adjusted CPUE data would result in a design flow with an even greater transition between high and low flow than with the simple CPUE dataset used in the original analysis. This expectation remains untested but underscores the need for a broader sensitivity analysis of methods (CPUE estimation) and shapes of design flows [as suggested originally in (*2*)].

As noted by Williams *et al.* (*1*) and Halls *et al.* (*3*), the monitoring effort at the Dai fishery was inconsistent (i.e., variable frequency and location of sampling across Dais, seasons, and years). Counts of monitoring observations by year and Dai row for the low- and high-migration periods (Tables 2 and 3) show that the median number of observations in each year ranged from 62 to 488 (median = 217) and 37 to 422 (median = 229) for the low- and high-migration periods, respectively. There was relatively low overall sampling effort in the first 2 years of the time series and among Dai rows 13 to 15 (rows farthest from Phnom Penh). We therefore investigated the effect of this limited sampling effort on the results by repeating our MARSS analysis factorially, removing the first 2 years and the last three Dai rows.

As before, the results remain robust whether or not these data are included (Table 4).

Our reanalysis with lunar adjusted CPUE data, as suggested by Williams *et al.* (*1*), preserves, and in fact strengthens, the central findings of Sabo *et al.* (*2*). Differences in how the Dai fishery monitoring data are adjusted for CPUE or total catch are ultimately a judgment call. The critical question, however, is whether these decisions influence the result of the time-series analysis in a meaningful way. The calculation of CPUE and lunar adjustment and subsequent reanalysis presented here found no substantive differences in the main results of (*2*), which suggests that trends in the data are strong relative to variation in scaling.

Finally, Williams and colleagues have repeatedly asserted (*1*, *5*, *6*) that Sabo *et al.* (*2*) advocate for dams to be built in the Mekong River. Holtgrieve *et al.* (*7*) rebutted this claim and we do so again here. The intent of our research is not to advocate for dam construction in the basin, which has been happening at a rapid pace in recent years regardless (*8*). Rather, we seek to understand the potential effects of dam reoperation for multiple purposes, including fisheries, and to explore opportunities to minimize negative impacts of existing dams. Given the ongoing development pressures, exploring options to mitigate the impacts of infrastructure development on food security is a pressing challenge in need of scientifically driven approaches like the one presented by Sabo *et al.* (*2*).

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28 February 2019; accepted 13 May 2019
Published online 7 June 2019
10.1126/science.aav9887

Table 1. Parameter estimates for density-independent MARSS models on historical hydrology and CPUE data. Results using the two datasets (Sabo et al. 2017 versus current approach) are compared.

Variable	Dataset	Coefficient	SE	Lower CL	Upper CL
Flood pulse extent (FPExt)	Simple CPUE (*2*)	1.080	0.313	0.467	1.693
	Lunar scaled CPUE	1.507	0.300	0.919	2.094
Net annual anomaly (NAA)	Simple CPUE (*2*)	−0.813	0.318	−1.437	−0.189
	Lunar scaled CPUE	−1.084	0.304	−1.680	−0.488

Table 2. Count of sampling events during the low migration period. Year is reported as the year when the fishing season concluded (e.g., 1996–1997 fishing season is listed as 1997).

Dai row	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
2	4	8	22	34	137	162	35	19	12	6	35	37	31	23	24	25	22
3	4	10	18	32	42	32	26	19	20	32	26	24	35	31	22	27	40
4	3	11	24	23	28	31	25	22	15	15	21	25	14	7	15	19	15
5	3	12	31	32	25	38	22	22	21	23	14	22	14	10	13	12	21
6	2	13	23	31	30	37	32	19	12	19	21	27	26	24	18	22	27
7	2	10	13	18	18	34	16	13	14	27	9	10	24	17	2	16	22
8	5	13	8	26	25	33	20	19	15	12	14	39	18	13	12	15	20
9	6	9	9	19	20	20	16	10	3	1	3	7	4	3	8	5	10
10	16	11	21	28	35	24	17	16	15	19	14	39	25	21	17	15	19
11	7	18	16	18	21	22	22	14	12	10	21	34	26	11	7	19	29
12	7	22	18	27	29	27	17	11	16	17	23	26	29	20	22	20	21
13	1	10	9	7	3	6	6	8	6	3	3	2	3	2	2	1	2
14	2	13	14	19	13	13	17	13	12	14	25	25	13	9	6	8	6
15	0	5	3	16	13	9	12	9	14	10	19	16	10	8	10	8	10
Sum of observations	62	165	229	330	439	488	283	214	187	208	248	333	272	199	178	212	264
Median number of observations	3.5	11	17	24.5	25	29	18.5	15	14	14.5	20	25	21	12	12.5	15.5	20.5
Max. number of observations	16	22	31	34	137	162	35	22	21	32	35	39	35	31	24	27	40
Min. number of observations	0	5	3	7	3	6	6	8	3	1	3	2	3	2	2	1	2

Table 3. Count of sampling events during the high migration period. Year is reported as the year when the fishing season concluded (e.g., 1996–1997 fishing season is listed as 1997).

Dai row	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
2	1	2	17	42	51	66	41	21	34	22	22	35	21	43	26	11	12
3	5	3	14	19	30	26	36	17	29	37	31	30	26	26	29	25	15
4	1	5	21	18	19	32	19	14	22	20	21	33	12	28	17	7	13
5	2	4	16	13	29	37	26	13	24	27	27	18	18	16	16	11	12
6	2	4	12	15	17	25	22	16	28	24	17	31	21	17	16	20	18
7	11	4	4	7	1	18	20	12	17	32	14	38	17	20	6	8	8
8	9	2	13	11	7	15	18	13	21	18	16	23	24	14	18	9	8
9	7	0	4	9	10	8	18	9	10	12	15	19	9	8	11	3	2
10	6	4	20	15	19	16	22	16	23	22	23	36	14	21	19	24	16
11	4	2	16	14	8	6	22	17	31	28	19	52	8	26	29	14	14
12	5	7	15	20	9	11	16	23	29	28	15	53	20	26	24	21	21
13	0	0	6	4	5	4	8	8	11	11	11	8	5	8	5	3	2
14	0	0	16	8	12	4	16	13	18	18	11	39	11	13	17	18	16
15	0	0	4	3	0	3	10	8	11	16	12	7	8	10	8	9	6
Sum of observations	53	37	178	198	217	271	294	200	308	315	254	422	214	276	241	183	163
Median number of observations	3	2.5	14.5	13.5	11	15.5	19.5	13.5	22.5	22	16.5	32	15.5	18.5	17	11	12.5
Max. number of observations	11	7	21	42	51	66	41	23	34	37	31	53	26	43	29	25	21
Min. number of observations	0	0	4	3	0	3	8	8	10	11	11	7	5	8	5	3	2

Table 4. MARSS reanalyses to test influence of years and Dai rows with low sampling effort.

Model	Covariate	ML.Est	Std.Err	low.CI	up.CI
All years (1997–2013), all Dai rows (2–15)	FloodPulseExtent	1.507	0.300	0.919	2.094
	netAUC	–1.084	0.304	–1.680	–0.488
All years, without Dai rows 13–15	FloodPulseExtent	1.432	0.395	0.658	2.205
	netAUC	–0.938	0.404	–1.729	–0.147

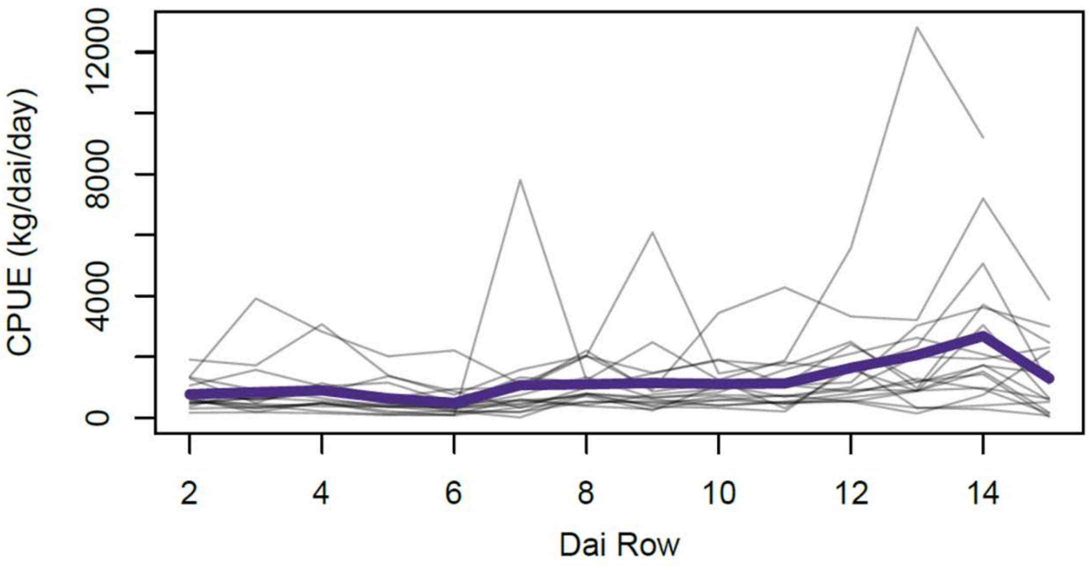

Fig. 1. CPUE among years 1997–2013 by Dai row. Light gray lines are CPUE for individual years; the purple line is the average among years.

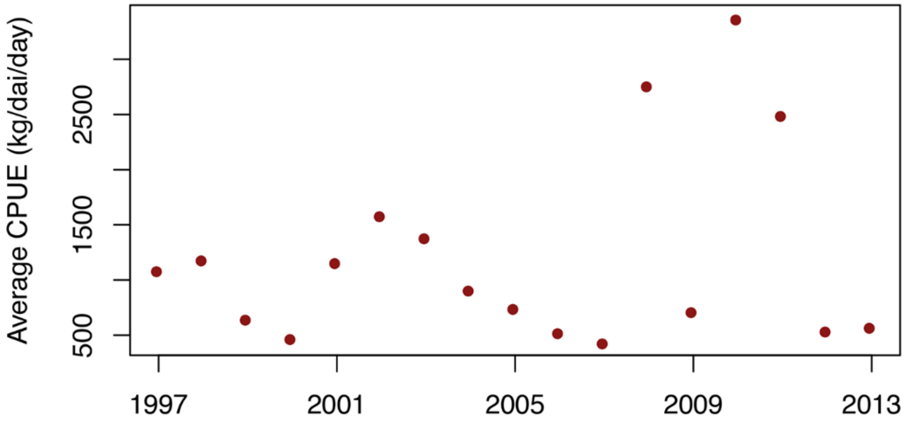

Fig. 2. Average CPUE across Dai rows for each year 1997–2013. Year is reported as the year when the fishing season concluded (e.g., the 1996–1997 fishing season is coded as 1997).

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Science **364** (6444), eaav9887.
DOI: 10.1126/science.aav9887