Flawed analysis greatly exaggerates streamflow response to forest clearing

A comment on Evaristo, J. & McDonnell, J. J. (2019), Global analysis of streamflow response to forest management. *Nature* **570**, 455-461, doi:10.1038/s41586-019-1306-0.

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In a recent Nature article[1], Evaristo and McDonnell (herafter E&M) compile a database of paired watershed studies, and use it to fit a gradient-boosted-tree model that predicts how streamflow responds to removal of forests. This model yields the surprising conclusion that streamflow response to forest removal is predominantly controlled by the total potential water storage in the landscape. E&M further conclude that removing the world's forests would contribute an additional 34,000 km^3 yr^{-1} to streamflow worldwide, nearly doubling global river flow of 40,700 km^3 yr^{-1} (Table 1 of ref. 1).

Here we show that none of this is valid. Spot checks of the database compiled by E&M reveal order-of-magnitude errors. The gradient-boosted-tree model that underlies E&M's conclusions is grossly overfitted, and fails rudimentary validation checks. The dominance of potential storage as an explanatory variable relies on a single extreme data point, and on a model profiling technique that is inconsistent with the source data. The global extrapolation of the model incorrectly assumes that Earth's entire land surface is forested, leading to massively exaggerated water yields, and even mass balance failures (total streamflow exceeding total precipitation) at continental scale.

Errors in the underlying database. We spot-checked seven lines of the database underlying E&M's analysis, and found three gross errors (we have not checked the rest of the database): 1) The Valtorto catchment in Portugal does not belong in a forest clearing database because it was not forested, but rather covered by 50 cm tall heath[2]. Furthermore, E&M's reported streamflow increase of 363.6 percent in response to clearing at Valtorto is inconsistent with Table 3 of the original reference[2], which reports that average streamflows increased from 1.0 to 2.5 m^3 day^{-1} (a 150 percent increase). 2) E&M report that streamflow at the PE10 catchment in Brazil ***decreased*** by 10 percent in response to clearing, but Table II of the original reference[3] shows that streamflow actually ***increased*** by 118 percent, from 170 to 373 mm yr^{-1} (E&M may not have noticed that the pre- and post-clearing discharge totals apply to different lengths of time). 3) E&M report that clearing the Lemon catchment in southwestern Australia increased streamflow by 631.8 percent. But from Table 1 of the original reference[4], we calculate that the average pre- and post-clearing streamflows were 18.0 and 27.9 mm yr^{-1} respectively; thus the increase following clearing was only 9.9 mm yr^{-1}, or 55 percent of the pre-clearing streamflow (and only 1.4 percent of the average precipitation during the study period). This gross overestimate disproportionately influences E&M's model, as described below. It also illustrates how E&M's decision to analyze percentage (rather than absolute) changes in streamflow exaggerates the impacts of harvesting in small arid catchments with near-zero streamflows.

Model overfitting and validation failure. Gradient-boosted trees – and the other machine learning tools that E&M tried but did not use – are data-hungry, and a database like E&M's (which includes just 161 forest clearing experiments) is orders of magnitude too small to reliably estimate their seven-variable model. The model codes that E&M published with their paper, and which underlie all their major conclusions, each contain 200 adjustable parameters (not counting the dozens of additional parameters that define the branch points), suggesting severe overfitting. This overfitting should be obvious in validation checks, but E&M presented none, so we randomly split the data into a training set and a validation set, each containing half of the points (80/20 splits yielded comparable results). We then re-ran the boosted-tree analysis, using the same platform (JMP, SAS Institute, Cary, NC, USA) and the same algorithm options that E&M used, for 300 of these random splits of the data.

The results in Figure 1 show that the model fails even this rudimentary validation check: the median R^2 is much smaller for the validation data than for the training data, and the root-mean-square error (RMSE) for the validation data is much larger than (and negatively correlated with) the RMSE for the training data. These patterns are diagnostic of badly overfitted models. Such models are predictively useless despite their nice-looking R^2 statistics, because they have been tuned to follow the noise in the training data. Essentially all of E&M's results are based on the boosted-tree model, so the validation failure demonstrated here (which also extends to the model that predicts the effects of planting; see Figure 1) invalidates every major conclusion of the paper.

Exaggerated importance of potential storage. The apparent importance of potential storage relies entirely on one highly questionable data point described above (Lemon catchment, Australia), which has both an erroneous (and implausibly high) percentage change in streamflow, and an extremely large potential storage (15 meters, more than twice the next-highest value in the data set). Removing this one extreme point completely eliminates the weak but marginally significant correlation (R^2=0.025, p=0.04) between potential storage and percent streamflow response. Likewise, if this one point is excluded from the boosted tree analysis, potential storage is no longer the most important variable. Furthermore, even with the full data set, potential storage does not emerge as a clearly dominant variable in the boosted tree analysis itself. To achieve that result (as shown in E&M's Figure 2b), E&M had to instead run an "independent uniform input" prediction profiler, invoking the counterfactual assumptions that the input variables are independent from one another and uniformly distributed between their minimum and maximum values (Figure 2). Both of these assumptions are inconsistent with the source data, and if they are not made, potential storage is no longer the dominant variable.

Gross exaggeration of global streamflow implications. To estimate the potential impact of forest clearing on global streamflow (Table 1 of ref. 1), E&M first apply their boosted tree model to a database of 442,319 catchments for which the required seven input variables are available (whether or not they are actually forested). E&M then multiply the median percentage change in streamflow for each continent's catchments, times the average continental river flow (see Extended Data Table 1). The fundamental error here should be self-evident: the potential percentage increase in streamflow from forest clearing cannot be applied to the entire continental runoff, because less than 30% of Earth's land area is forested[5]. It should have been obvious that something was wrong: for example, under E&M's median scenario, their Table 1 implies that total runoff in Asia would be

14,550+16,062=30,612 km^3 yr^{-1}, or 95% of total Asian precipitation (32,140 km^3 yr^{-1})[6], a runoff ratio that is rarely observed even in urban areas (see Extended Data Table 1). For Australia, the results in E&M's Table 1 even violate conservation of mass, with total post-clearing runoff (1,970+5,412=7,382 km^3 yr^{-1}) exceeding total precipitation (6,405 km^3 yr^{-1})[6]. Likewise it is hard to know what to make of E&M's claim (Figure 5 and following text) that one would gain particularly large water yields from deforesting tropical grasslands or deserts, neither of which are densely forested in the first place.

It is not difficult to obtain more reasonable global estimates of potential forest clearing effects. Globally, evapotranspiration from forests is roughly 250 mm yr^{-1} greater than from croplands or grasslands[7], and multiplying this difference by the 40 million km^2 of global forests[5] yields a rough estimate of 10,000 km^3 yr^{-1}, less than one-third of E&M's result. Even this may be an overestimate, because the lower evaporation rates of grasslands partly reflect the fact that they often occur in drier climates; thus the difference between forest and grassland evaporation may exaggerate the effects of converting forests to grasslands.

Concluding remarks. To mention just one other troubling aspect of E&M's analysis, they choose to ignore the obvious importance of the percentage change in forest cover as a driver of water yield response, equating 1-percent and 100-percent felling. Their rationale is that "the correlation between treatment area and water-yield response… is known to be weak (R^2=0.17)"[1]. Consistent application of this criterion would have eliminated every variable in E&M's data set, because they all exhibit *even weaker* correlations with water-yield response.

We do not have space in this short note to address every problem in E&M's analysis. Likewise we have not discussed the other model fitting methods that they presented but did not ultimately use, many of which suffer from similar issues to those presented here. Nonetheless, the problems that we have identified are glaring and consequential, and would have been detected by even the most cursory checks. On this basis we conclude that the paper's results cannot be trusted, and that retraction is warranted.

Readers should keep in mind that this is not a purely academic exercise. How much, and under what conditions, forests should be cleared is an important policy question with wide-ranging consequences for economies, societies, and ecosystems. In that regard, E&M's conclusion that "forest removal can lead to increases in streamflow that are around 3.4 times greater than the mean annual runoff of the Amazon River" is profoundly misleading. The Amazon flows continuously, but the water yield benefits of forest clearing are transient, typically lasting only a few years, or at most decades, after felling[8]. One must also keep in mind that the water transpired by vegetation is an important source of precipitation farther downwind, estimated to account for roughly 40% of continental precipitation[7]. Thus repeated large-scale clearing of forests would predictably lead to precipitation decreases and drying of continental interiors, although the precise magnitude of this effect remains difficult to constrain.

Data availability statement. All of the data analyzed here are available as described in the data availability and code availability statements of ref. 1, or from the cited references.

Author contributions statement. All authors discussed the issues raised here, and contributed to the writing. J.W.K. analyzed the data and prepared the first draft.

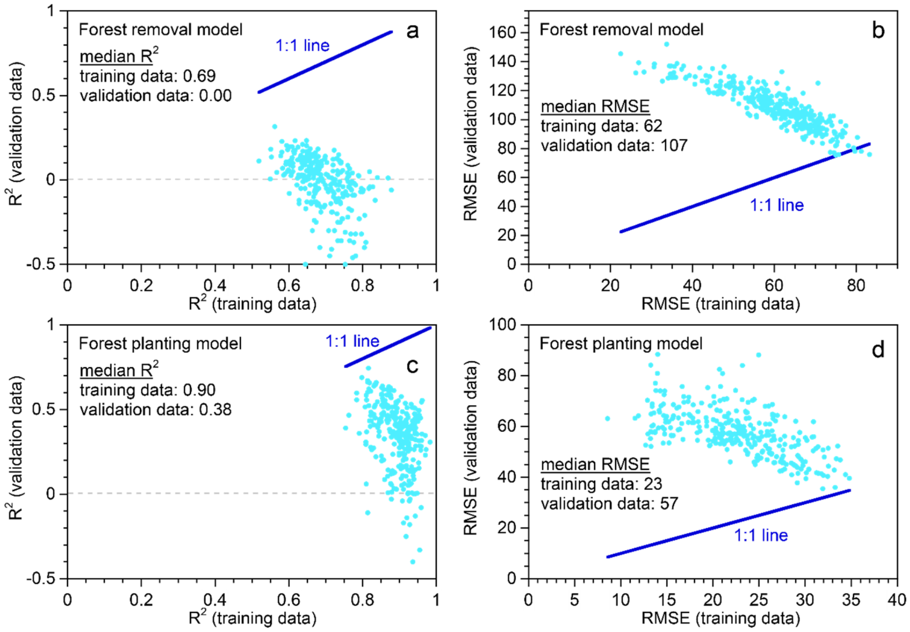

Figure 1. Split validation tests of Evaristo and McDonnell's gradient-boosted-tree models for forest clearing (a, b) and forest planting (c, d). The source data were randomly split into 300 training and validation sets, each comprising half of the data. If the model were not overfitted, the R^2 (a, c) and root-mean-square error, or RMSE (b, d) statistics obtained from the validation and training sets would be similar to one another; they would lie close to the 1:1 lines. Instead, the R^2 statistics (a, c) for the validation data are systematically much smaller than for the training data (additional points with validation R^2 less than -0.5, indicating that the model was much worse than random guessing, are not shown). Rather than clustering around the 1:1 line, the RMSE statistics for the validation data are much larger than, and inversely correlated with, those for the training data (b, d). The patterns shown here are diagnostic of badly overfitted models.

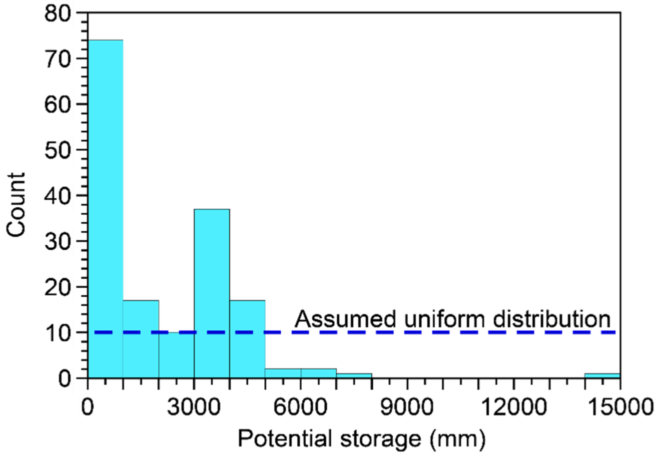

Figure 2. Distribution of potential storage in Evaristo and McDonnell's database, compared to the uniform distribution used to estimate its influence on their model. Potential storages exceeding 5000 mm comprise less than 4% of Evaristo and McDonnell's data set (light blue bars), but 67% of the distribution used to calculate the influence of potential storage in their model (dark blue dashed line), greatly exaggerating the importance of potential storage.

Extended Data Table 1. Modeled effects of forest cover change on continental runoff

Region	Total river runoff[1]	Change in runoff in response to forest-cover change[1] (km^3 yr^{-1})		Total river runoff after removal[2]	Total precipitation[3]		Change in runoff in response to forest-cover change (%)[4]			Median water yield in complete catchment data set (%)[5]	
	(km^3 yr^{-1})	Planting	Removal	(km^3 yr^{-1})	(km^3 yr^{-1})		Planting	Removal		Planting	Removal
Africa	4,320	-605(1,944)	8,986(5,616)	13,306	20,780		-14.0(45.0)	208.0(130.0)		-14(45)	208(130)
Asia	14,550	-1,979(5,835)	16,062(25,783)	30,612	32,140		-13.6(40.1)	110.4(177.2)		-14(40)	110(177)
Australia and Oceania	1,970	-412(725)	5,412(4,962)	7,382	6,405		-20.9(36.8)	274.7(251.9)		-21(36)	275(252)
Europe	3,240	-875(1,102)	813(1,426)	4,053	7,165		-27.0(34.0)	25.1(44.0)		-27(34)	25(44)
North and Central America	6,200	-806(2,034)	918(2,102)	7,118	13,910		-13.0(32.8)	14.8(33.9)		-13(33)	15(34)
South America	10,420	0(3,751)	1,908(17,559)	12,328	28,355		0.0(36.0)	18.3(168.5)		0(36)	18(168)

Values with parentheses show medians (and interquartile ranges).

[1] From Table 1 of ref. 1.

[2] Sum of total river runoff and median change due to removal.

[3] Total precipitation from ref. 6, which is also the original source of the total river runoff values.

[4] Median and IQR runoff changes, as percentage of total river runoff.

[5] Median and IQR of water yield predictions (each rounded to the nearest percent in the published database) for E&M's 442,319 "complete" catchments. These agree within roundoff error with the percentages calculated by dividing the change in runoff by the total runoff for each continent. This agreement demonstrates that the changes in runoff shown in Table 1 of ref. 1 were calculated by multiplying the median (and IQR) water yield predictions by the total river runoff, rather than the runoff from forested areas.

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