TECHNICAL RESPONSE

SUSTAINABILITY

Response to Comment on "Planetary boundaries: Guiding human development on a changing planet"

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Jaramillo and Destouni claim that freshwater consumption is beyond the planetary boundary, based on high estimates of water cycle components, different definitions of water consumption, and extrapolation from a single case study. The difference from our analysis, based on mainstream assessments of global water consumption, highlights the need for clearer definitions of water cycle components and improved models and databases.

Jaramillo and Destouni (*1*) argue that the planetary boundary for global freshwater use, currently proposed to be 4000 km^3 $year^{-1}$ of consumptive use (henceforth "consumption") of runoff (*2*), has already been transgressed. We welcome their assessment, which suggests that our planetary boundary update for freshwater (*3*) may be too conservative. Their analysis employs an auxiliary calculation from an earlier study (*4*), not considered by Steffen *et al.* (*3*), which suggests a global freshwater consumption of 4485 km^3 $year^{-1}$. This value is substantially higher than the ~2600 km^3 $year^{-1}$ estimate used by Steffen *et al.* (*3*), derived from well-established global assessments (*5*–*9*). We note that Jaramillo and Destouni accept the position of the freshwater planetary boundary but question our quantitative estimate of current human freshwater consumption—i.e., the proximity to the boundary. Their higher estimate of global freshwater consumption is based on four grounds.

First, they suggest that evaporation from hydropower reservoirs—1257 km^3 $year^{-1}$ globally (*1*, *4*)—is well above earlier findings. This higher number is based on an estimate of changes in landscape-driven evapotranspiration (ET) calculated by comparing long-term time series of changes in actual ET flows (derived from precipitation and runoff observations) with estimates of climate-driven changes in ET flows from temperature observations. This indirectly derived net ET change is assumed to originate from increased ET around reservoirs resulting from raised groundwater levels and altered atmospheric conditions. Such a large influence from hydropower dams was not included in our studies (*2*, *3*), although basin-scale calculations in Steffen *et al.* (*3*) accounted for reservoirs and their evaporation to derive downstream effects on river flow and water use.

Second, Jaramillo and Destouni assume that consumption of "blue" water from rivers, lakes, reservoirs, and aquifers for irrigation currently amounts to 2600 km^3 $year^{-1}$ (*10*). The value for blue water consumption used in Steffen *et al.* (*3*), which represents an upper end of other estimates (*5*–*9*), is as high but includes industrial and domestic water consumption.

Third, Jaramillo and Destouni argue that ET from agricultural areas of "green" water (precipitation water in the soil that evaporates or transpires through plants), estimated to be 3628 km^3 $year^{-1}$ (*4*), is part of human water consumption. Yet, as they acknowledge, this amount is countered by the ET flow that would occur anyway (i.e., if agricultural areas were still covered by natural vegetation); hence, they consider only a fraction of it anthropogenic—i.e., 628 km^3 $year^{-1}$—based on a comparison with an earlier study (*10*). These different components together with industrial and municipal water consumption yield the total 4485 km^3 $year^{-1}$ [figure 1 in (*1*)].

Fourth, the new estimates of reservoir evaporation and green water ET (*1*) are coarse extrapolations from a single Swedish case study to the global scale (*4*). Scaling factors are based on Swedish dam capacity per hydropower production and the cultivated fraction of Sweden's total land area, respectively. The underlying assumption is that hydrogeological conditions, groundwater table positions, agricultural intensification rates, and associated ET changes around the globe are comparable to conditions in Sweden.

While Jaramillo and Destouni argue that their high estimate of global reservoir evaporation may even be conservative, it requires corroboration by similar investigations for reservoirs worldwide. Nevertheless, even if their number turns out to be more accurate, total global blue water consumption (the control variable for the freshwater boundary) is still likely to be lower than 4485 km^3 $year^{-1}$. The reason is that the model-based estimate of global irrigation water consumption they use is, to our knowledge, by far the highest reported in the literature [2600 km^3 $year^{-1}$ (*10*)]; studies based on sophisticated dynamic models and statistical data indicate a range of ~1200 to 1700 km^3 $year^{-1}$ (*11*). This difference may partly stem from the fact that the Gordon *et al.* (*10*) estimate implicitly includes ET of green water from irrigated land, which may be substantial (*11*). Moreover, we think that applying an uncertainty range (±380 km^3 $year^{-1}$) on top of this high-end estimate (*1*) is inappropriate. Ultimately, the reported differences point to the need for exact definitions and consistent calculation of water balance components.

Furthermore, the Jaramillo and Destouni analysis includes both green and blue water consumption, whereas our control variable for the planetary freshwater boundary strictly includes blue water consumption only (*2*, *3*). The rationale is that blue water is regarded as an aggregate indicator of the interplay of both green and blue water flows in the hydrological cycle, in that an alteration of green water flows (upstream) typically induces shifts in blue water availability (downstream). Therefore, it remains important to keep the calculations of the two apart. Combining them naturally leads to a higher estimate of total consumptive use, which must not be compared to the current boundary value.

Finally, we stress that the present boundary value of 4000 km^3 $year^{-1}$ embodies uncertainties. It has been argued earlier that it may be "too generous" (*12*), although another study (*13*) suggested that it may be higher or lower, depending on how environmental flow requirements of river ecosystems are calculated (which are key to estimating both the position of the planetary boundary and the value of the control variable). We conclude that Steffen *et al.* (*3*) do not convey a "message of apparent calm" (*1*) regarding human water consumption; on the contrary, they reaffirm earlier findings that human interference with water systems is well above local tolerance limits, notwithstanding that a planetary boundary is not yet transgressed. Ultimately, a systematic reassessment is necessary of both the boundary value and the total human freshwater consumption, based on an internally consistent model and data framework.

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