Letter to the editor re: "The scarcity-weighted water footprint provides unreliable water sustainability scoring" by Vanham and Mekonnen, 2021

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1. Introduction

In their recent paper "The scarcity-weighted water footprint provides unreliable water sustainability scoring", Vanham and Mekonnen (2021) criticize scarcity-weighted water footprints as "contraproductive for achieving SDG target 6.4". Unfortunately, the paper is another example of an unproductive dispute between the life cycle assessment (LCA) and water footprint (WF) communities, which mainly deals with the question whether the water footprint should be a volumetric or environmental impact-based indicator. In the past, this led to a series of "reply to" papers such as Hoekstra et al. (2009) replying to Pfister and Hellweg (2009) commenting on Gerbens-Leenes et al. (2009), or Hoekstra and Mekonnen (2012a) replying to Ridoutt and Huang (2012) criticizing Hoekstra and Mekonnen (2012b). Some of the key issues addressed in this reply have been more generally raised by Pfister et al. (2017) in a reply to a critique of the LCA concept.

As recently stated in Gerbens-Leenes et al. (2021), we agree that this conflict between the communities has been unhelpful, even if science needs a debate. Authors of this letter to the editor have been involved in several discussions leading to the recognition of the complementarities of the two approaches (Boulay et al. (2013), Gerbens-Leenes et al. (2021), Boulay et al. (2021)) and continue to strive for scientific relevance in the use of different approaches. This letter aims at 1) clarifying methodological misunderstandings concerning impact-based water scarcity footprints, 2) revealing methodological shortcomings in the analysis of Vanham and Mekonnen (2021), and 3) showing that volumetric and impact-based water footprints can answer relevant but different questions related to water use along supply chains.

2. Misunderstandings about water scarcity footprint

2.1. Equation of the water scarcity footprint calculation

Do we square the blue WF in the water scarcity footprint calculation (Eqs. (1) and (2) in Vanham and Mekonnen (2021))? No, it is not done. This is a misunderstanding that has been clarified in the response to the same critiques that Hoekstra (2016) raised against the LCA based WF (Pfister et al., 2017). Here we briefly explain the actual meaning of the water scarcity footprint calculation in a new attempt to resolve the confusion.

For water scarcity footprints in LCA, the impact on water scarcity is assessed by multiplying two terms, namely (1) the WF inventory (i.e. blue water consumption) of the system under study with (2) a characterization factor that represents the potential environmental impact of water consumption in the area (e.g. in a watershed). Depending on the water scarcity method adopted, different aspects of water scarcity can be addressed, such as the pressure on ecosystems, human needs, or both (Kounina et al., 2013). The first blue water consumption term (WF inventory) is the blue water consumption of the system under study, and the second term is the blue water scarcity that represents how the blue water resources are pressured by all human activities in the target area (including not only the system studied but all water consumption by all activities, similar to the background concentration used for emissions' impact assessment in LCA). In that sense, the meanings of blue WFs in eqs. 1 and 2 in Vanham and Mekonnen (2021) are different. The blue WF in Eq. (1) should represent the total water consumption in an area by all human activities. The first term of Eq. (2) should be the blue water consumption by the product (1 ton of wheat in their case). Therefore, the water scarcity footprint in LCA does not square the amount of water consumed by the product system but weighs the water consumption amount of the target product with the scarcity condition of the area considering the current situation.

As for any model, the modeling of environmental impacts in LCA is based on a series of assumptions. One of these assumptions is that, although exceptions exist (see below), LCA typically assumes marginality of the inventory in relation to the local background situation represented in the characterization factor. A marginal model quantifies the impact that an additional unit of water consumption (the inventory) has on top of the background situation (used for the characterization factor), where the background situation is not significantly altered by the system analyzed.

In reality, as AWARE (Boulay et al., 2018) and any other LCA scarcity indices are built, the inventory contributes an infinitesimal (i.e. marginal) amount to the total water consumption in the watershed. Thus, the marginal approach is an acceptable assumption to characterize small-scale interventions, for instance, water consumption in a plot of wheat as long as the blue WF of growing this wheat is small enough relative to the background water consumption in the watershed. To assess medium- and large-scale water consumption, such as considering the overall water demand of agricultural production in a watershed, the marginal approach becomes unsuitable. Non-marginal approaches should be used instead, as being able to capture substantial alteration of the background hydrological setting. The application context for the use of marginal versus non-marginal characterization factors has been discussed in the LCA literature, with some articles focusing on water footprint assessment (Scherer and Pfister, 2016; Heijungs, 2020; Huijbregts et al., 2011; Boulay et al., 2020; Forin et al., 2020; Pfister et al., 2020).

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2.2. Physical meaning of the water scarcity footprint

Does the water scarcity footprint have no physical meaning? As explained above, the water scarcity footprint represents the potential environmental impacts caused by the amount of water consumed on the basis of an indicator of scarcity. Indicators of scarcity, i.e. a characterization factor in LCA, take various forms (Kounina et al., 2013; Liu et al., 2017; Boulay et al., 2018). The meanings of scarcity indicators differ but can be categorized into two types: based on relative or absolute availability.

Regarding relative availability-based indicators, the existing ones represent the pressure of overall consumptive water use to the available water resources in the target area, mostly with the ratio of consumptive water use to the availability, following the same logic as SDG indicator 6.4.2. Thus, the water footprint, calculated as the water consumption weighted by a relative availability-based indicator, characterizes the severity of water consumption in the area in terms of water competition that may potentially restrict the utility for other users. On the one hand, this presents the benefit that both volumetric and competition aspects of water resources can be considered simultaneously. On the other hand, there is an implicit assumption in this approach that the degree of change of consumed volume and a relative availability-based indicator has the same significance in the potential impacts on other users, regardless of the environmental background being considered (e.g. arid or non-arid).

Regarding absolute availability-based indicators, the physical meaning of the water scarcity footprint is clearer. The AWARE model by Boulay et al. (2018), which is recommended on the basis of the international consensus under the umbrella of UNEP (Jolliet et al., 2018; Boulay et al., 2021), is an indicator based on absolute availability. AWARE stands for “available water remaining”, which is calculated by subtracting humans' and ecosystems' water demands from a basin's water availability. To account for the basin's size, the volume of available water remaining is divided by the basin's area. Thus, the physical meaning of the AWARE indicator is the area needed to sustainably generate 1 m^3 of water for each watershed and month. For deriving the AWARE characterization factors to be used in LCA or for a water scarcity footprint, the absolute availability-based indicator is then normalized with the value at the global level. This is similar to what is done for greenhouse gas emissions' radiative forcing normalized against the one of a kg of CO_2 over a certain time horizon. Therefore, when using the characterization factor, the value of the water scarcity footprint represents the equivalent volume of water that has the same impact from a water consumption at the global level. Finally, the values are cut off at a factor of 100 times above the global average to avoid potentially indefinitely high or negative results, which indicate a situation of extreme overuse. Another cut-off at 10 times below the global average was applied, and thus the AWARE scarcity indicator ranges from 0.1–100 global m^3 equivalent per ^{m3} of water consumed.

Water scarcity in LCA can also be addressed with reference to so-called three areas of protection, namely: human health, ecosystems, and resources. In this case, the physical meaning of a water scarcity footprint is more straightforward because the available models assess the potential damage of water consumption on human health (Pfister et al., 2009; Boulay et al., 2011; Motoshita et al., 2011; UNEP, 2016; Motoshita et al., 2018), ecosystem quality (Pfister et al., 2009; Hanafiah et al., 2011; van Zelm et al., 2011; Verones et al., 2013; Verones et al., 2017; Damiani et al., 2021) and resource depletion (Mila i Canals et al., 2008; Pfister et al., 2009). Therefore, the value of a water scarcity footprint based on these damage level scarcity indicators explicitly represents the damage to humans (as potential life years lost), ecosystems (as potential habitat or species loss) or resources (as potential energy requirements for desalination) due to water consumption of the product system.

The physical meaning of the blue water stress index (BWSI) adopted by Vanham and Mekonnen (2021) is also clear (Hoekstra and Mekonnen, 2012a; Mekonnen and Hoekstra, 2016) as it defines a binary state of conceptual overuse or not. In principle, it follows the same logic as the relative availability-based indicator described above, but instead of reporting it on a continuous function, it reports based on a binary function. The choice of the function is normative and not conceptually different regarding the underlying assumption (i.e. the more water is used compared to availability, the less sustainable it is). The physical meaning of the WF based on the BWSI is the amount of consumed water that exceeds the boundary of sustainable water use like other studies on the planetary boundaries (Rockström et al., 2009; Steffen et al., 2015). However, the severity of the over-consumed water depends on the balance of the excess of consumption from the carrying capacities and the amount to be left for sustainability of the environment, which differs among watersheds even if the amount of exceeded water consumption is the same (Motoshita et al., 2020). In this sense, both the WF based on the BWSI and the water scarcity footprint complement each other from different dimensions towards the same goal of sustainable water use.

2.3. Methodological shortcomings of the analysis

The paper by Vanham and Mekonnen (2021) draws conclusions based on results achieved under methodological shortcomings, which warrants caution. Since the authors do not share the data, it is difficult to follow their criticism, and we respond here within the limits of how they chose to present the results.

The analysis builds on modeled yields and blue and green volumetric WFs of crop production from Mekonnen and Hoekstra (2011). The main issue that hampers a meaningful use of that data for this analysis is that the yield is calculated for grid cells as a function of water availability and demand (on a grid cell level) in combination with national average yield values for each crop and country (multiplied by a factor of 1.2, to account for yield gaps). Consequently, the yields of a low-productivity area are overestimated, and the yields of high-productivity areas are underestimated. This is important for water productivity calculations and Vanham and Mekonnen also acknowledge it, as they write “Setting a global blue WF benchmark for irrigated wheat does not make sense, because a benchmark blue WF depends on the climate zone it is produced in”. Likewise, using a national average yield is not meaningful if there are significantly varying climate conditions (which is the case for most countries). This might also explain the very high water productivity of 2 kg/m^3 in their example of points 1 and 2 in their Fig. 2, a potential artifact of the underlying data. Similar data on high spatial resolution and crop level, providing green and blue water consumption data (Pfister et al., 2011), are based on modeled yields on grid cell level and might lead to a different result. That study also calculates a range of water consumption reflecting the uncertainty of such global models, which are high.

Also related to the data, the researchers state that they “compute for 248,654 grid cells whether irrigated wheat is produced sustainably or unsustainably within a grid cell.” However, based on the underlying data, the grid data contains the “irrigated fraction of harvested crops” and, therefore, it is not clear how irrigated and non-irrigated crops within a grid cell have been separated.

They analyze their Fig. 1 as follows: “In total the 56,915 sustainable grid cells are ranked over a range of 1 to 139,115 (Fig. 1c). The 191,739 unsustainable grid cells are ranked over the whole range from 1 to 248,654. This thus means that up to the rank of 139,115, a substantial amount of unsustainable grid cells receives a better ranking than many sustainable grid cells.” However, their definition of sustainability is normative based on statistical thresholds without physical meaning, especially for efficiency, which is calculated based on the water requirements of both irrigated and rain-fed agriculture without considering the variability of environmental and technological contexts (e.g. fertilizer use and diversity in agricultural practices). Furthermore, the choice of setting the benchmark at the 50th percentile seems rather arbitrary considering that Mekonnen and Hoekstra (2014) identify the largest increases in the water footprint of wheat from the 80th–90th percentile. These sources of uncertainty would be far less relevant if water productivity were actually used to assess the potential water savings of individual production systems over time, as is the case in Mekonnen and Hoekstra (2014), rather than to compare different (modeled) systems and assign arbitrary sustainability scores.

Additionally, using the binary classification of sustainable vs. unsustainable limits the power of the analysis drastically. Their sustainability scheme leads to categorical variables. Within the four categories, there can still be high variation, which is hidden by the categorization. It would be impossible to make choices between products or production regions within such a broad category. As such, the sustainability scheme would be useless for decision-making in many cases. Even if products or production regions fall within different categories, the strict cut-offs could lead to unreasonable conclusions. This especially applies if a value is just below or above the threshold (like in their example of point 1 in their Fig. 2 with a water stress index of 0.98, which could as well exceed the threshold of 1, considering the uncertainties in the underlying data). Proper understanding of the relationship between the two indicators would require a pairwise analysis or a correlation analysis.

The analysis in their Fig. 2 compares different sustainability metrics. The mismatch of the indicators is mainly caused by the addition of green to blue water on the y-axis. Otherwise, the differences would be much smaller (as also demonstrated by the better match in their Fig. 5 compared to Fig. 3). Additionally, the analysis is done “for a sample of irrigated wheat grid cells”, but it remains unclear how the sample was derived, which could be biased. The supported conclusion is that not all low water productivity happens in highly irrigated areas and that not all irrigation occurs in water-stressed regions. There is no conflict; this is just what happens in the world. Besides, this is the result of an analysis between regions and not a comparison for the same environmental condition. At the same place or grid cell, reducing scarcity should also help to protect water resources and enhance efficiency - unless green water is used inefficiently.

In the second approach, they compare water productivity, based on data from national statistics, to benchmarks for aridity zones. This means production in a drier area of the same aridity zone would have lower water productivity than from a wetter area of the same aridity zone when assuming the same yield - just because it needs more irrigation. This is not a meaningful comparison when dividing the data into only four aridity zones.

Importantly, with this paper, Vanham and Mekonnen aim to criticize the water scarcity footprint as used in LCA and described in the ISO 14046 guideline (ISO 14046), while the scarcity-weighted water footprint they use in their analysis does not conform to the LCA calculation methodology. Therefore, their analysis does not support the conclusions they draw. In their Eqs. (1) and (2), they define scarcity-weighted footprint as the square of blue water consumption divided by environmentally available blue water resources. However, the blue water consumption of the system under study (inventory) and the water scarcity (impact assessment) cannot be assumed to be the same. Their concern about the reliability of water scarcity footprint results published in high profile journals such as Science (Poore and Nemecek, 2018) and PNAS (Clark et al., 2019), on the basis of the outcomes of their study is neither supported by an analysis of the same case studies nor by a comparison between the methodologies adopted by Vanham and Mekonnen (2021) and those adopted by Poore and Nemecek (2018) and Clark et al. (2019), which are markedly different, as they are based on the AWARE model (Boulay et al., 2018).

3. Complementarity of water scarcity and efficiency and the scarcity-weighted water footprint

Vanham and Mekonnen (2021) claim that “the scarcity-weighted WF provides inconsistent scoring results with respect to water stress and water efficiency”. The previous section on “Methodological shortcomings of the analysis” has already elaborated on causes for perceived inconsistencies as a result of the choices in the modeling. Still, the question of whether water use efficiency, water scarcity, and the scarcity-weighted WF are at odds or complementary remains and shall briefly be discussed in this section.

Water scarcity as a standalone indicator has the sole purpose of reflecting water demand relative to water availability within a spatial unit, such as a watershed (see also SDG indicator 6.4.2). It shows the status of specific watersheds. Water efficiency considers product systems and supports water resources management within a limited region of similar water scarcity. As mentioned in previous sections, the scarcity-weighed WF focuses on global product systems and combines water scarcity values of relevant watersheds (i.e. the characterization factors) with irrigation water efficiencies (i.e. the inventoried water consumption per unit of product). Considering a complete value chain of a product and comparing different products, the characteristics of water efficiency and water scarcity can differ between value chain stages (from process to process). When we separately look at water efficiency and water scarcity, we can identify the crucial stages from either aspect. However, the crucial stages may not necessarily be the same for water efficiency and water scarcity, leading to trade-offs between the two, as is explained in FAO's guideline on assessing water use and discussion paper on water productivity in livestock production (FAO, 2019; Drastig et al., 2021).

The multiplication of the water consumption volumes with the associated water scarcities can help to compare the potential impacts of crops grown in regions of different climatic zones independently from the farmer's performance using e.g. average consumption per region (FAO, 2019). It serves to determine potential impacts along global supply chains and can also be suitable for detecting regions where the growth of specific crops might be unfavorable in general. Water efficiency based on benchmarks, on the other hand, excludes this aspect (FAO, 2019). It solely judges water efficiency based on the average performance in a region (or median as in Vanham and Mekonnen, 2021) and neglects that some regions could also be unfavorable for specific crops. However, it has the strength to put the performance of a farmer within the context of specific regions. Thus, it can be used complementary to a water scarcity-weighted footprint to verify if identified hotspots show any site-specific water-saving potentials (FAO, 2019). It is important to note that water consumption above the benchmark does not necessarily lead to negative consequences. There could be cases where a farmer might show a relatively low performance compared to the regional benchmark, but water is abundant in the basin where the crops grow. Or it might be grown on marginal land and therefore counteract deforestation of more productive areas. From the impact assessment perspective, there would be no adverse impact, but the water quantity sustainability scheme by Vanham and Mekonnen would still declare the production as unsustainable.

Considering China's wheat production, for instance, high or low water efficiency (the total water productivity or blue water productivity) can occur in both water-rich and water-scarce regions (Huang et al., 2019). The scarcity-weighted WF, which combines water efficiency and water scarcity, can directly reflect the environmental relevance of water consumption. High scarcity-weighted WF values indicate low efficiency or high water scarcity or both, highlighting the need for more urgent actions.

In conclusion, the scarcity-weighted WF is not an indicator contradictory to the approach by Vanham and Mekonnen (2021). On the contrary, the scarcity-weighted WF is a complementary indicator (Drastig et al., 2021) that enables an overarching view of water efficiency and water scarcity. Hence, the three indicators (water scarcity WF, water efficiency and volumetric WF) are not meant to be consistent with each other, but rather to be complementary.

4. Conclusion

“The scarcity-weighted water footprint provides unreliable water sustainability scoring” is yet another paper that is symptomatic of an unproductive dispute between the WF and LCA communities.

It contains methodological misunderstandings about the water scarcity footprint. The two main points that we have clarified are first that there is no squaring of the blue WFs, but rather a multiplication of a product system's water consumption with the characterization factor expressing local water scarcity. Second, there is a physical meaning of water scarcity footprints, which denote how severe water consumption in the area is in terms of competition for water or express the potential damages on human health, ecosystems or natural resources, depending on the impact assessment method used.

In addition to these misunderstandings concerning water scarcity footprints, we identified several methodological shortcomings which weaken the conclusions of Vanham and Mekonnen, among which we highlight key issues here.

Finally, we think it is counterproductive to play off volumetric and impact-based water footprints against each other. Volumetric footprints allow for analyzing water efficiency - and are sometimes complemented by an analysis of local scarcity, as shown in Fig. 2 of Vanham and Mekonnen (2021). Water scarcity footprints combine volumetric and scarcity-related information and express potential local impacts, which can be compared with another region's impacts. As both indicators answer relevant but different questions, we acknowledge the relevance of both of them and recommend using them complementary rather than in competition with each other.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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