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Supplementary Material

Complementary Strengths of Water Footprint and Life Cycle Assessments in Analyzing Global Freshwater Appropriation and its Local Impacts – Recommendations from an Interdisciplinary Discussion Series

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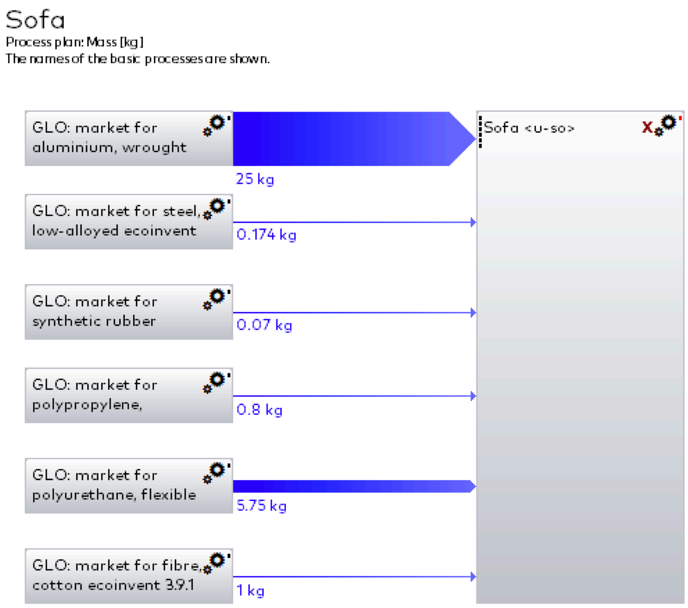


Figure S 1. Screenshot of the GaBi model of the Sofa

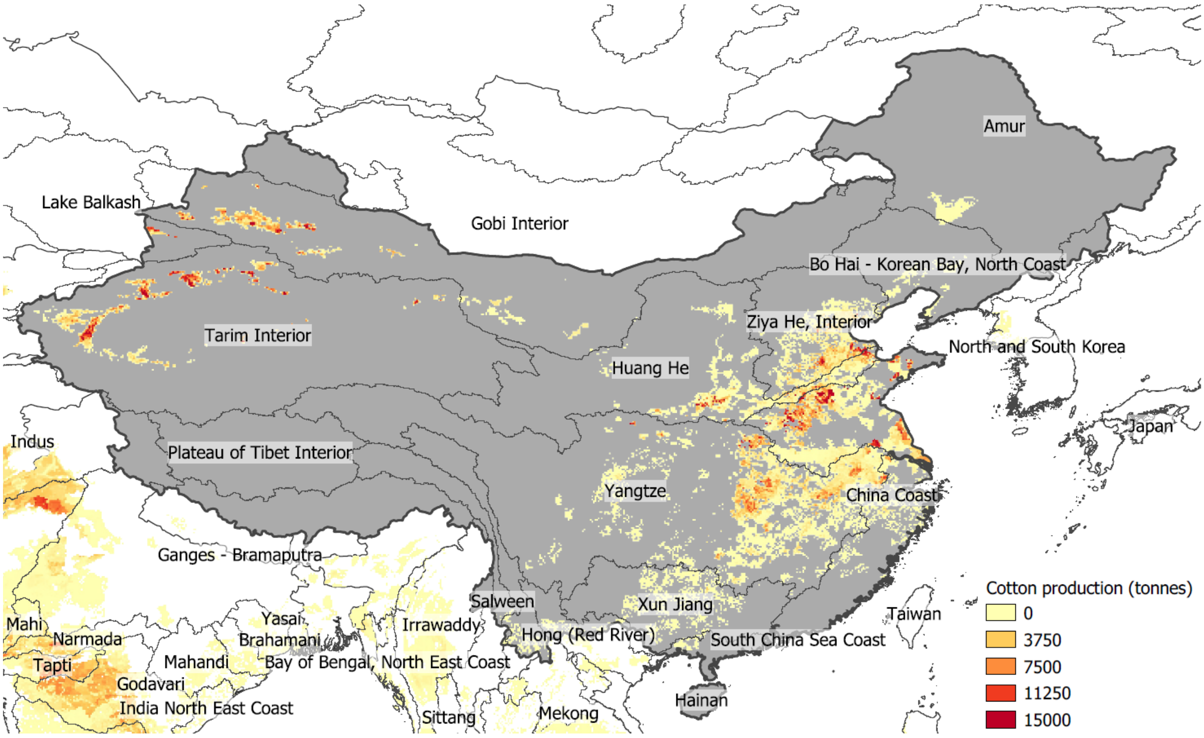


Figure S 2. Gridded cotton production overlayed with major river basins

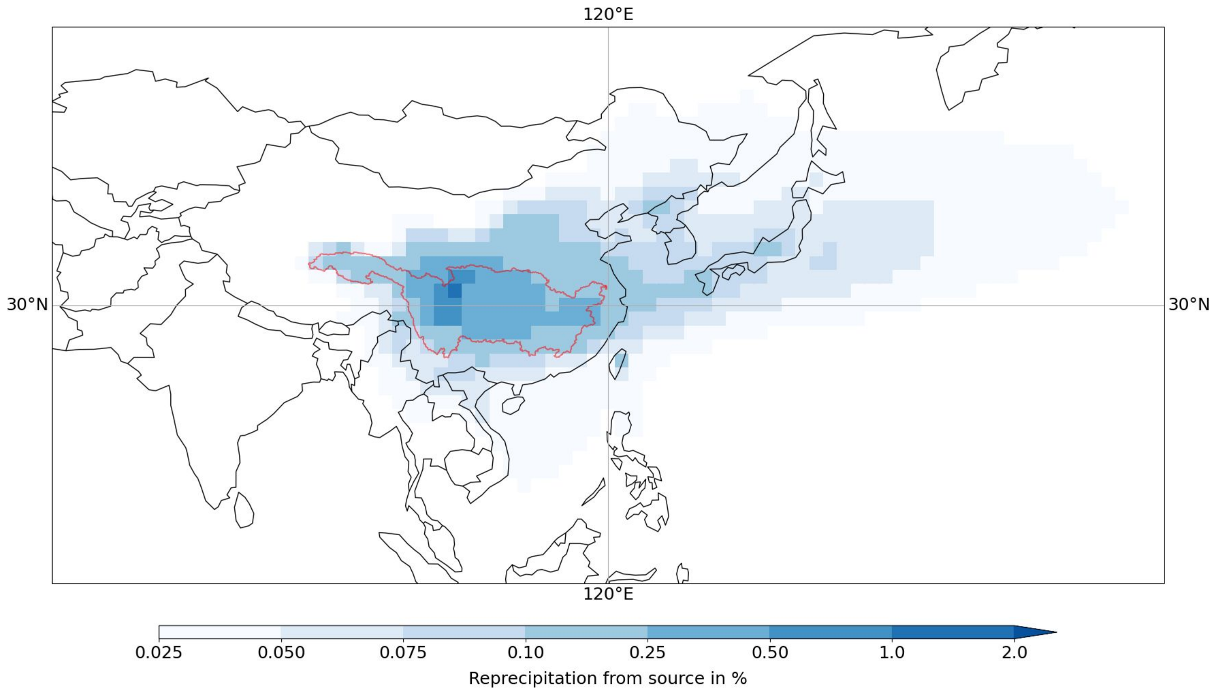
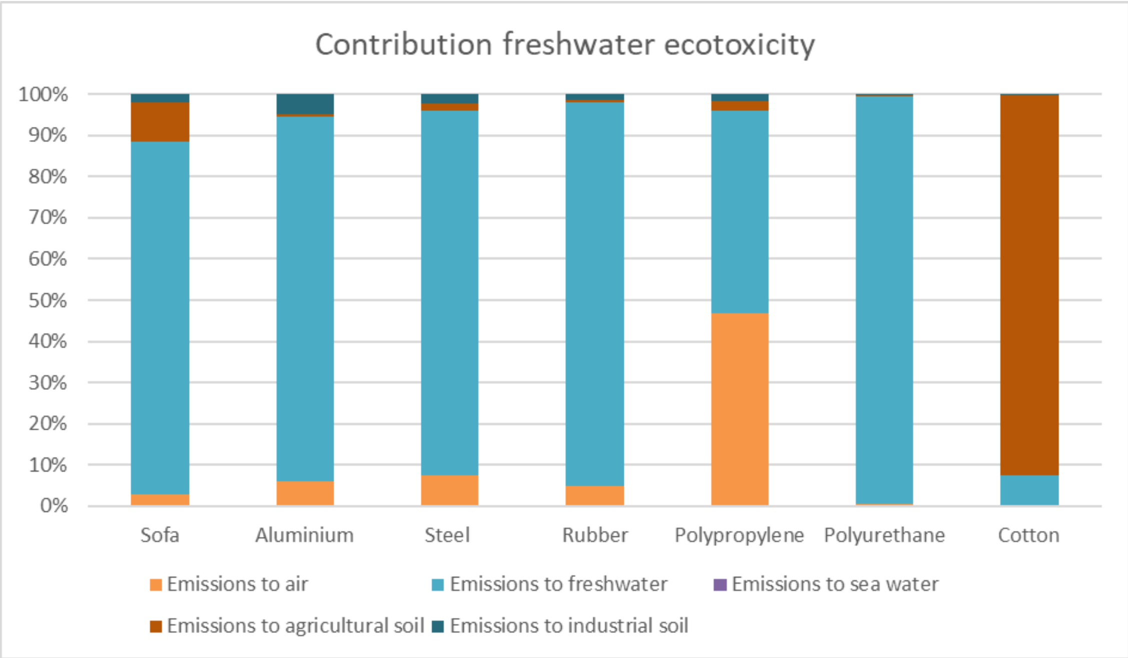
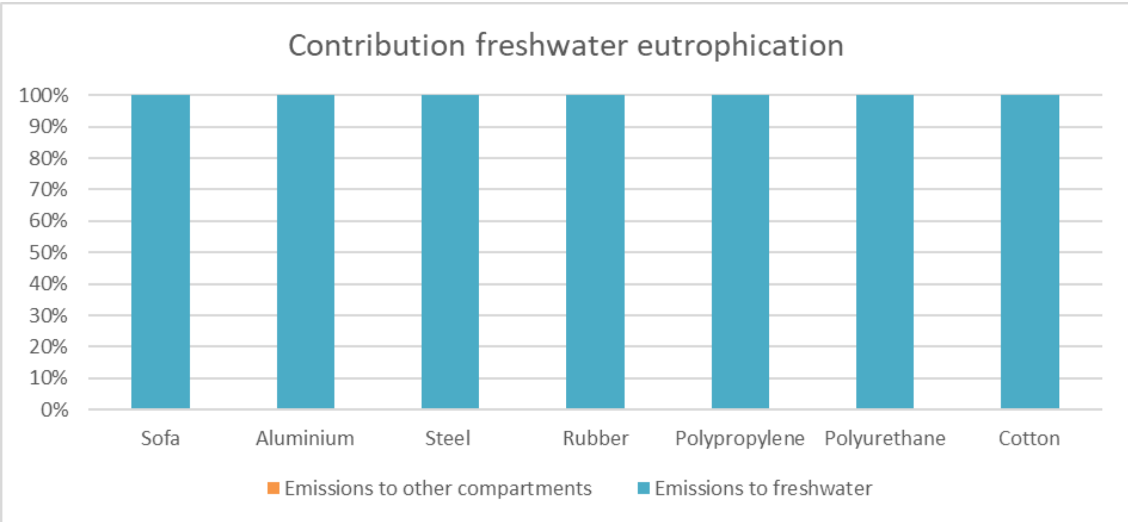


Figure S 3. Average core areas of reprecipitation of evaporation from a sample basin (Yangtze basin; outlined in red); the coloured area represents grid cells where at least 0.025% of reprecipitation takes place and covers approx. 74% of the tracked moisture



a)



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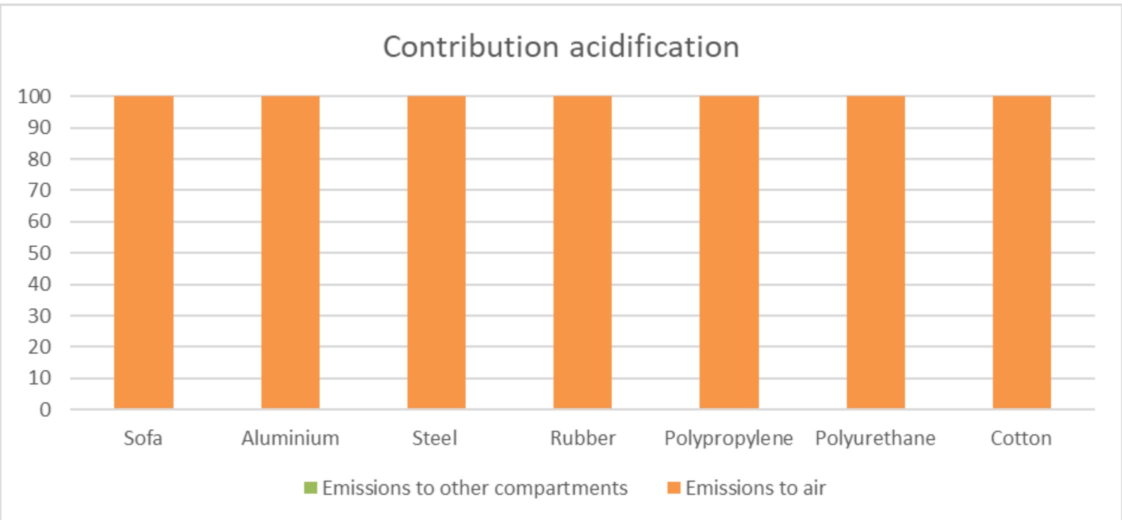

c)

Figure S 4. Contributions of emissions to different environmental departments to the results of the impact categories a) freshwater eco-toxicity, b) freshwater eutrophication, and c) acidification

Tables

Table S 1. Total, green and blue water consumption per tonne of raw cotton produced in the top 11 producing countries

Country	**WF tot m³/t**	**Green**	**Blue**	**Production Mt**	**Share in global production**
China, mainland	1037	669	368	19.0	26%
India	3741	2771	970	16.9	23%
United States of America	2263	1673	590	10.9	15%
Pakistan	3453	1021	2432	5.2	7%
Brazil	1209	1201	8	4.6	6%
Uzbekistan	2597	390	2207	2.9	4%
Turkiye	576	575	1	2.5	3%
Australia	1737	681	1056	1.7	2%
Greece	1479	1153	327	0.8	1%
Mexico	1620	437	1183	0.8	1%
Turkmenistan	6973	337	6636	0.8	1%
Average	2283	1421	862		
Total				66.1	89.6%
			Global	73.7	

S1: LCA methods addressing effects of green water consumption

Table S 2. LCA methods addressing effects of green water consumption: only addressed conceptually (1/3); partially operational method (2/3) but no global coverage; fully operational method (3/3) with global coverage

Relevant green water aspects covered	Heuvelmans et al., 2005	Maes et al., 2009	Saad et al., 2013; Bos et al, 2016	Lathuillière et al., 2016	Núñez et al., 2013	Quinteiro et al., 2015, 2018	Link et al., 2021	Sonderegger et al 2020
effects on average (blue) water availability	X (1/3)		X (3/3)			X (3/3)	X (3/3)	
effects on (blue) water scarcity	X (1/3)	X (1/3)				X (3/3)	X (3/3)	
erosion			X (3/3)					X (3/3)
compaction								X (3/3)
flooding	X (1/3)							
water purification effects			X (3/3)					
contribution to the atmospheric moisture flux		X (1/3)		X (2/3)	X (2/3)	X (3/3)		
atmospheric moisture fluxes coupled with precipitation feedback				X (2/3)		X (3/3)	X (3/3)	

All methods relate the impacts of land transformation and occupation to a reference situation of a PNV and the main LCA database Ecoinvent sees green water as a part of land use rather than a separate inventory flow (Pfister et al., 2016). Heuvelmans et al. (2005) initially proposed extending life cycle methodology to assess land use system impacts on regional water balances. Their conceptual approach included inventorying changes in surface runoff, infiltration, evaporation, and precipitation due to land use changes. They suggested an impact category, "regional water balance" encompassing effects on water availability, flooding, and drought risks. Maes et al. (2009) proposed using PNV as the reference, arguing that it represents the condition of maximal ecosystem services. Changes in evaporation were seen to negatively affect atmospheric moisture flux or on-site freshwater availability. While they suggested calculation rules for low-data impact assessments, no ready-to-use characterization factors were provided. Saad et al. (2013) used four indicators for assessing water-related impacts of land cover changes: groundwater recharge, erosion resistance, and physicochemical and mechanical filtration for water purification. They provided globally applicable characterization factors for various biogeographic regions and considering seven land use types while considering both land occupation and transformation. Spatially differentiated characterization factors were derived using nine input parameters on soil, landscape, and climate, processed with the LANCA tool (LANd use indicator value Calculation), which is currently the only available method in LCA for characterization of land-use-induced impacts on water (Bos et al., 2016). The model proposed by

Lathuillière et al. (2016) assesses land and water use in seasonally dry, semi-arid and arid regions with tightly coupled precipitation and evaporation. Potential downwind precipitation reduction under land cover change was addressed and then applied to a case study in the Amazon region. While no global factors were provided, the authors highlight the general transferability of the method to other regions. Núñez et al. (2013) examined net evaporation changes on an inventory level, without detailing specific impacts of green water change beyond the overall water balance. They offered green water flows for PNV in global drylands. The introduced method by Quinteiro et al. (2015) assess impacts on atmospheric green water flows and address critical reductions in surface blue water production. They further tried to provide operational characterization factors for both pathways on a global scale (Quinteiro et al., 2018). Link et al. (2021) proposed a conceptual water inventory scheme that highlights the interrelationships between blue and green water resources. With respect to the fate of evaporated water, global factors describing the precipitation feedback and the potential recharge of blue and green water resources in remote regions could be described. Thus, the factors can also be used to describe potential impacts of (green) water evaporation on blue water availability and scarcity on a global scale. A further method assesses impacts of compaction and water erosion (Sonderegger et al., 2020).

S2: Do WFA and LCA speak the same language?

To set the ground for answering this question, the terminology sections of two reference documents are considered: the Water Footprint Assessment Manual (Hoekstra et al., 2011) and ISO 14046 (2014). The focus will be on those terms that are identical or similar in both documents but differ in meaning.

Differences can already be found in the basic definition of the term water footprint. In WFA it is defined as "an indicator of freshwater use that looks at both direct and indirect water use of a consumer or producer", which is "measured in terms of water volumes consumed (...) and/or polluted per unit of time". This footprint term can be further qualified to identify the type of water used (green, blue, grey) or to indicate the subject of the study (e.g. product, organization, nation). In ISO, the water footprint describes a "metric(s) that quantifies the potential environmental impacts related to water." This definition clarifies that ISO focuses on the local consequences of water use (comprising water consumption, water pollution, or both) and on the impacts of other activities affecting water resources (e.g. emissions of SO_2 to air which can result in freshwater acidification) along supply chains. Accordingly, an aggregation of volumetric water consumption would not be termed water footprint in LCA, but water footprint inventory. The term water footprint is only used when an impact assessment step has been conducted and when all the potential impacts are addressed. If a narrower assessment is accomplished that should be identified by means of qualifiers, e.g. water scarcity footprint or water acidification footprint. It should be noted that ISO does not define the terms green, blue, and grey water.

Another term with a different meaning is water scarcity. In the case of WFA, it is defined as the ratio of water consumption over water availability, where availability is understood as the amount of physically available water that can be sustainably used by humans, i.e., without harming ecosystems. Water for nature is therefore a priori set apart by subtracting environmental flow requirements from natural runoff. Scarcity in WFA can refer to both green and blue water resources. In the case of ISO, water scarcity is based on the concept of demand (which can be different from withdrawals) compared to the replenishment of water in an area (without reserving water for ecosystems). The term water availability is also defined differently in ISO as an "extent to which humans and ecosystems have sufficient water resources for their needs". So according to ISO, in contrast to water scarcity, water availability can also be influenced by water quality.

Further differences have been detected concerning the term water use. In ISO, it is defined as "use of water by human activity" which includes water withdrawal and discharge – but also "in-stream uses such as fishing, recreation, or transportation". In WFA, the term water use is not defined explicitly – but described within the definition of the term water footprint as volumes of water consumed and/or polluted. The related term of water consumption is defined equally in both standards as the share of water use which is not returned to the originating basin due to evaporation, transpiration, product integration, or discharge into other basins or the sea.

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