Titre: Title:	Complementary strengths of water footprint and life cycle assessments in analyzing global freshwater appropriation and its local impacts – Recommendations from an interdisciplinary discussion series
Auteurs: Authors:	Markus Berger, Winnie Gerbens-Leenes, Fatemeh Karandish, Maite M. Aldaya, Anne-Marie Boulay, Rick J. Hogeboom, Andreas Link, Alessandro Manzardo, Oleksandr Mialyk, Masaharu Motoshita, Montserrat Núñez, Stephan Pfister, Ralph K. Rosenbaum, Laura Scherer, Han Su, & Lara Wöhler
Date:	2025
Type:	Article de revue / Article
Référence: Citation:	Berger, M., Gerbens-Leenes, W., Karandish, F., Aldaya, M. M., Boulay, A.-M., Hogeboom, R. J., Link, A., Manzardo, A., Mialyk, O., Motoshita, M., Núñez, M., Pfister, S., Rosenbaum, R. K., Scherer, L., Su, H., & Wöhler, L. (2025). Complementary strengths of water footprint and life cycle assessments in analyzing global freshwater appropriation and its local impacts – Recommendations from an interdisciplinary discussion series. Ecological Indicators, 174, 113458 (20 pages). https://doi.org/10.1016/j.ecolind.2025.113458

Ecological Indicators 174 (2025) 113458

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Review

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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ARTICLE INFO

Keywords:
Water footprint
Water use
Water management
Supply chain management
Environmental impacts

ABSTRACT

Considering globally increasing water challenges, the analysis of water use along supply chains is of great relevance and can be tackled by mainly two methodological approaches: Water Footprint Assessment (WFA) and Life Cycle Assessment (LCA). While sharing the same goal of promoting sustainable water use, both methods developed in different contexts and scientific communities. This has led to heated debates on methodological presuppositions that at times has become unconstructive. To build mutual understanding and enable a fruitful cooperation, researchers from both communities have exchanged over the course of two years. This paper summarizes the outcomes of this discussion series by providing i) a description of the development of both approaches and their ways of assessing freshwater consumption and pollution, ii) an application in a case study, and iii) an analysis of strengths and weaknesses in relation to questions decision-makers may have. Our analysis revealed that WFA's strength lies in its ability to measure freshwater appropriation, water-use efficiency, water scarcity and total pollution levels. This makes WFA particularly useful for crop selection as well as agricultural and river basin water management. With its focus on assessing impacts, LCA is strong in quantifying potential consequences of water use for humans and ecosystems. This makes it particularly useful for assessing complex supply chains and for analysing water-related impacts in combination with other environmental aspects. Rather than being in competition with each other, we emphasize the individual and complementary strengths of both approaches and their joint efforts in addressing the world's pressing water challenges.

Abbreviations: BEER, Basin External Evaporation Recycling; BIER, Basin Internal Evaporation Recycling; CF, Characterization factor; EF, Ecological footprint; GHG, Greenhouse Gas; GWS, Green Water Scarcity; GWC, Green Water Consumption; LANCA, Land use Indicator Value Calculation; LCA, Life Cycle Assessment; LCI, Life Cycle Inventory; LCIA, Life Cycle Impact Assessment; Net GWCeff, Effective Net Green Water Consumption; PNV, Potential Natural Vegetation; WFA, Water Footprint Assessment; WF, Water Footprint; RER, Rest of Europe; RoW, Rest of the World; SETAC, Society of Environmental Toxicology and Chemistry; SDG, Sustainable Development Goals; SM, Supplementary Material; UN, United Nations; WS, Water Scarcity; WSF, Water Scarcity Footprint.

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https://doi.org/10.1016/j.ecolind.2025.113458
Received 13 December 2024; Received in revised form 4 April 2025; Accepted 4 April 2025
Available online 10 April 2025

1. Introduction

1.1. Background & goal

At the UN 2023 Water Conference, the United Nations concluded that “Water is a dealmaker for the Sustainable Development Goals (SDG), and for the health and prosperity of people and planet” (UN, 2023a). However, despite this relevance, the world’s “progress on water-related goals and targets remains alarmingly off track, jeopardizing the entire sustainable development agenda” (UN, 2023a). Within SDG 6 on clean water and sanitation, the indicators on water use efficiency (6.4.1) and water stress (6.4.2) show that water is used more efficiently on global average (+9%), but also that global water stress is not decreasing as expected (+1%) (UN, 2023b). This can be explained by an increase in total production and consumption patterns of water-intense goods, which, together with effects of climate change, has led to increasing water stress levels – especially in already water-scarce regions (UN, 2023b).

This development illustrates the relevance of understanding water use along agricultural and industrial supply chains as well as its local consequences on ecosystems and humans. Two prominent methods aiming to provide such insights on water footprints (WFs) to consumers, companies and policy are Water Footprint Assessment (WFA) and Life Cycle Assessment (LCA). Even though both approaches share similar goals and methodological frameworks (Fig. 1), they have been developed in different contexts and by different scientific communities. This has led to a persistent debate on methodological settings (e.g. Hoekstra, 2016; Ridoutt and Huang, 2012) and on their suitability to serve SDG 6.4 to increase water-use efficiency and ensure freshwater supply (e.g. Pfister et al., 2022; Vanham and Mekonnen, 2021). The most controversial points, which are discussed in more detail throughout this paper, are: i) the consideration of green water; ii) the focus of assessing blue water consumption on the volumetric level (WFA) or on the level of the resulting potential environmental impacts by means of water scarcity footprints (LCA); and iii) the consideration of freshwater pollution in either grey WFs (WFA) or specific impact categories (LCA). Since this debate has caused confusion among practitioners and decision-makers and “has proven to be very unhelpful”, researchers from the WFA and LCA communities have recently called for “joint efforts to tackle the increasing global water challenges together” (Gerbens-Leenes et al., 2021). As a result, a series of online meetings were held between November 2022 and October 2024 in which sixteen researchers equally representing the WFA and LCA communities discussed methodological settings and the suitability of both approaches for different use cases.

This paper summarizes the outcomes of this consensus-finding process by first presenting the development of WFA and LCA in their respective scientific domains (chapter 1.2), which explains the background of different methodological settings. Subsequently, the methods to analyze water consumption and pollution, as well as similarities and differences, are described (chapter 2). Further, both approaches are applied in a case study to illustrate the practical implications (chapter 3) before application-dependent recommendations for practitioners as well as decision-makers are provided, common future research needs are identified (chapter 4) and conclusions are drawn (chapter 5). The novelty of this article compared to similar ones published previously lies in that (i) it presents a collaborative effort between both communities, necessitating the development of mutual understanding of each approach; (ii) it includes thoroughly discussed and agreed-upon application recommendations and shared future research needs.

1.2. Historic development

Environmental awareness started to scale up in the 1960s when environmental sciences gradually developed from disciplinary into multidisciplinary research focussing on local, regional and especially global environmental problems. This included e.g. the depletion of the ozone layer, climate change, acidification or air and water pollution. Addressing and communicating these problems required quantitative tools to assess the environmental interferences of production and consumption systems, including Life Cycle Assessment (LCA) (e.g., Boersema et al., 1984), Material Flow Analysis (e.g., Van der Voet, 1996), energy analysis (e.g., Blok, 2007) or footprint assessments (e.g., Rees, 1992). These tools share the principle of life cycle thinking, i.e. a consideration of environmental consequences along complete value chains, comprising raw material production, manufacturing, distribution, use, and recycling (or disposal).

1.2.1. History life cycle assessment

The first studies applying life cycle thinking date back to the 1960s and focused on cumulative energy accounting for chemical products in 1963 and Coca-Cola beverage containers in 1969 (Hunt and Franklin, 1996). During the 1970 s the method came to be called “Resource and Environmental Profile Analyses (REPA)” or “Ecobalance”, essentially applying and comparing material and energy accounting of products (US-EPA, 1974). Based on these approaches the method “Life Cycle Assessment” was introduced in the 1990s (SETAC, 1991) and spurred a

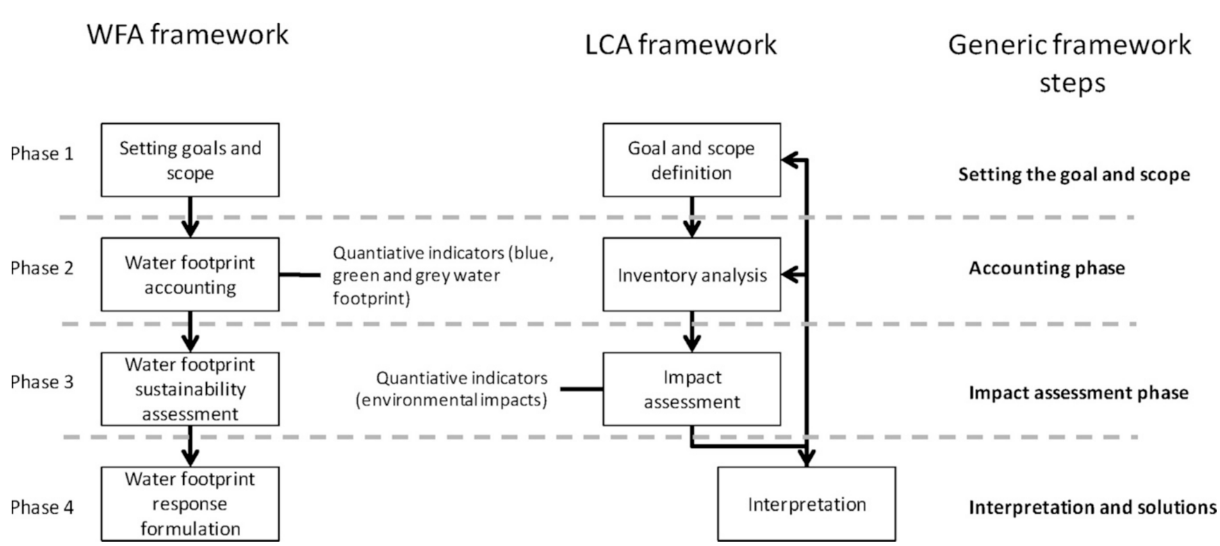

Fig. 1. Methodological frameworks of WFA and LCA, reproduced from Boulay et al. (2013).

largely uncoordinated method development in the US and Europe, particularly in Switzerland, The Netherlands, Germany, Denmark and Sweden during the 1980s and 90s (e.g., Frischknecht, 1998; Guinée et al., 1993; UBA, 1999). To harmonize this development and provide an internationally agreed and accepted framework for LCA, a set of four ISO standards (ISO 14040–14043) was developed during the late 1990s, which has been summarized and revised into the two ISO standards (ISO 14040, 2006a; ISO 14044, 2006b) valid until this day. Since then, methodological development continued, with increasing attention for global scientific consensus building on central parts of the LCA methodology – most notably under the umbrella of the Society of Environmental Toxicology and Chemistry (SETAC) and the UNEP Life Cycle Initiative (UNEP, 2024). Around 2010, the European Commission started to develop the Product Environmental Footprint (PEF) – a method based on LCA but with the goal of reducing flexibility and increasing comparability (EC, 2013), to be used as a basis for European legislation.

LCA applications initially included product improvement, new product design, product information, ecolabelling, and product exclusion or admission to the market. This product and production focus of earlier LCA applications became broader as more societal actors beyond industry, such as governments and NGOs, discovered and applied LCA, seeking science-based decision-making, thereby adding consumption, organizational, political and territorial perspectives, e.g., for policy formulation, implementation and evaluation to the spectrum of LCA applications.

With regard to water use, LCA traditionally focused on water pollution, expressed by means of impact categories such as eutrophication, acidification or eco- and human toxicity. The very first Life Cycle Impact Assessment (LCIA) method was published in 1984 (Bundesamt für Umweltschutz, 1984) and assessed degradative water use based on the concept of "critical volumes" (ratios of airborne and waterborne emissions to corresponding political thresholds). Water consumption was typically neglected or only quantified in the inventory as volumes of water consumed but without assessing the potential impact (Berger and Finkbeiner, 2010). With an increasing application of LCA to renewable raw materials, biofuels, or food products, this changed and a broad range of methods assessing potential local impacts of water consumption was developed (Kounina et al., 2013), as discussed in the following sections.

1.2.2. History water footprint assessment

Footprint assessments share the principles of life cycle thinking but have a different starting point. While LCA started as a tool to assess environmental impacts of specific industrial product systems, the focus of footprint assessments was typically on the consumption or appropriation of natural resources (e.g., land, materials, and water) for human purposes on a larger scale (e.g., sectors or nations).

The concept of the land footprint was introduced in the 1960s and referred to as “ghost acreage” (Borgstrom, 1965), used to describe the area of land abroad that is used to grow feed for animals within a country. About three decades later, the ecological footprint (EF) was introduced, which included a first footprint quantification methodology (Rees, 1992). The EF aimed to quantify the land resources needed to fulfil human consumption requirements, including the land needed to absorb carbon dioxide emissions related to this consumption.

In the 1970s, Tony Allan introduced the concept of virtual water. He noted that the increasing food needs in the Middle East had caused this region to run out of water. But rather than the predicted wars on water, countries started to import water-intensive agricultural commodities, thus making use of water resources elsewhere (Allan, 1998). Based on this concept, Arjen Hoekstra and colleagues introduced the water footprint concept (Hoekstra and Hung, 2002), to denote the freshwater appropriation of processes, products, organizations, consumers, and geographically delineated areas such as river basins or nations. According to the WFA method (Hoekstra et al., 2011), a WF measures the consumption of green water (precipitation), blue water (ground and surface water) as well as the degradative grey WF defined as a hypothetical amount of freshwater needed to assimilate polluted water to accepted water quality standards.

In the first decades of life cycle thinking-based method development, LCA and footprint analyses developed in parallel and to a large degree independently from each other in different scientific communities and for different purposes. Since the late 2000s, also LCA-based footprint methods have emerged for carbon (GHG Protocol, 2011; ISO 14067, 2018) and water footprints (ISO 14046, 2014), which, in contrast to the original methods, focus on impacts resulting from greenhouse gas (GHG) emissions and water use, respectively.

2. Methods to assess water consumption and pollution

This section describes how the two communities assess the consumption and pollution of freshwater and discusses commonalities and differences. It first discusses blue and green water consumption separate from water pollution, before an overarching discussion on commonalities and differences for all three types of water use is provided. In both communities and throughout this paper, the term water consumption is defined as the fraction of water use which does not return to the originating river basin. Consumption happens in case of water being evaporated, incorporated into a product, or discharged to another river basin or the sea (Bayart et al., 2010). Water use is a more generic term and can refer to consumptive water use (water consumption), degradative use (water pollution), borrowing use (no change in quality), as well as off-stream use (water withdrawal) and in-stream use (e.g. hydropower).

2.1. Blue water

2.1.1. Blue water in WFA

The blue WF is a spatially and temporally explicit indicator denoting the consumption of blue water resources that can be linked to a human activity and which is expressed in volumetric units (Hoekstra et al., 2011). A blue WF can be further differentiated for more specific blue water sources and origins, such as surface water and ground water, but this is not often done. Volumetric blue WF accounts are contextualized for potential impacts in a sustainability assessment, which can take different perspectives.

To assess the environmental sustainability of a blue WF, blue water scarcity is the most often used impact indicator. Scarcity, however, is a system property that emerges as the sum of the blue WFs of multiple users within that system—typically a catchment area—in relation to water availability in that system. Therefore, for WFs that refer to individual activities (companies, products, or consumers) the sustainability assessment entails assessing whether or not constituent parts of the blue WF are located in water-scarce catchments, and what their contribution is to that collective blue WF.

Another perspective in assessing sustainability refers to the frugal use of scarce resources and seeks to address the question of whether blue resources are being used efficiently. For this purpose, WFA formulates WF benchmarks per water-using activity, which give a reference value of a reasonable unit WF (in m^3/unit) for the activity or aggregate at hand, both for blue and total WFs (Mekonnen and Hoekstra, 2014). If a WF exceeds this WF benchmark, it means water is not being used efficiently, and therefore this WF is considered unsustainable in WFA. In theory, entire basins or countries can be contextualized for their resource use efficiency. But since these WFs refer to collective rather than individual or composite activities, the efficiency assessment is typically expressed as the share in the total blue WF of activities within the catchment that do not meet their respective WF benchmark values.

In case of assessing the sustainability of a blue WF of a consumer or group of consumers, another sustainability dimension can be assessed, namely the distributional equity of appropriated blue water resources. Given the emphasis in WFA on the global dimension of water through its embedding in internationally traded commodities, WFs of consumers (in

m^3/cap) can be compared to global fair and/or sustainable shares (Rockström et al., 2023).

2.1.2. Blue water in LCA

While also analyzing blue water consumption at the inventory level, the focus of LCA is on assessing the local, potential impacts resulting from this consumption. For this, blue water consumption occurring in different regions ($m^3_{region\ i}$) is multiplied by a spatially and temporally explicit characterization factor (CF, impact/$m^3_{region\ i}$) and aggregated into an impact-based WF. This is in line with other environmental impact categories, such as climate change, in which different GHG emissions (CO_2, CH_4, N_2O, etc.) are multiplied by a substance-specific CF (kg CO_2-equivalents/kg GHG) and aggregated to an impact-based carbon footprint (ISO 14067, 2018). While the CFs in carbon footprinting usually express the global warming potential of different GHGs (IPCC, 2021), CFs for water consumption typically denote local freshwater scarcity (Berger et al., 2018; Boulay et al., 2018; Frischknecht et al., 2009; Pfister et al., 2009). The underlying hypothesis is that the potential to deprive other users from using water (and thus the resulting impact) is increasing with increasing water scarcity.

A key assumption in LCA is that the volume of water consumed by the product system under study is marginal compared to the total water consumption of the basin (Boulay et al., 2013). That is, the water consumption of the study unit does not change the overall water scarcity in the basin and, thus, does not affect the CF. With an increasing application of LCA in sectoral or even territorial studies, this assumption may not hold true, and in such cases non-marginal CFs should be used (Boulay et al., 2020; Forin et al., 2020).

Next to the scarcity-based impact assessment methods described above, other methods model cause-effect chains which link blue water consumption to potential damages on:

- Human health due to malnutrition (Boulay et al., 2011; Motoshita et al., 2018; Pfister et al., 2009). These methods assume that depending on local scarcity and wealth, non-agricultural blue water consumption can lead to reduced irrigation capacities in agriculture, which leads to reduced crop yields, which leads to reduced nutrient supply (locally or in importing countries) and finally to malnutrition-based health impacts.
- Human health due to infectious diseases (Boulay et al., 2011; Debarre et al., 2022; Motoshita et al., 2011). Depending on local scarcity and wealth it is assumed that water consumption leads to reduced water availability for hygiene, which favours the spreading of infectious diseases leading to loss of human health.
- Terrestrial ecosystems (Lathuillière et al., 2016; Pfister et al., 2009; van Zelm et al., 2011). It is assumed that blue water consumption affects either the blue or green water availability for plants and therefore leads to a loss of terrestrial biodiversity.
- Freshwater ecosystems (Damiani et al., 2018; Hanafiah et al., 2011; Pierrat et al., 2023a). These methods model the effects of blue water consumption leading to reduced river run-off which reduces (or changes) the biodiversity of aquatic freshwater species.
- Wetlands (Amores et al., 2013; Verones et al., 2013). Depending on local scarcity, blue water consumption is assumed to lower the groundwater table which affects the biodiversity of groundwater-dependent wetlands.
- Freshwater resources (Mila i Canals et al., 2008; Pfister et al., 2009; Pradinaud et al., 2019). In basins in which water consumption or persistent degradation is higher than availability, the depletion of freshwater stocks and the resulting consequences for future generations are modelled.

As these methods model impacts at the end of a cause-effect chain, they are referred to as endpoint or damage models. In contrast, the scarcity-based impact assessment methods are called proxy-midpoint methods because they use scarcity as a proxy for generic impacts in the middle of the cause-effect chain.

Endpoint models allow for more meaningful indicators expressing potential damages on typically three so-called areas of protection (human health, ecosystems, and resources). They also allow for comparing (and aggregating) these damages to damages caused by water pollution and other non-water-related environmental interferences (e.g., GHG emissions or land use change), whose cause-effect chains are modelled in a similar and consistent manner. However, model and parameter uncertainty increase when modelling complex cause-effect chains and therefore, comparisons of endpoint impact assessment results are typically done at the level of orders of magnitude. Also, endpoint results should not be misinterpreted as absolute predictions but rather considered as potential and relative impacts, allowing for an identification of relevant processes and environmental interferences in complex supply chains.

2.1.3. Commonalities and differences

When comparing the approaches to measure and evaluate blue water consumption, it can be seen that both approaches start with quantifying the volumes of blue water consumed in a spatially and temporally explicit way. Based on this accounting or inventory, both approaches add an interpretation step to address the sustainability of consumption in a local context. However, the focus and procedure of this interpretation differs: WFA contextualizes volumetric WFs in relation to local scarcity, efficiency, and distributional equity, while LCA multiplies local water consumption by a CF to derive an impact-based WFs. Despite these differences, both approaches clearly acknowledge the relevance of: i) determining water consumption volumes in a spatially and temporally explicit way; and ii) adding meaning to these volumes by means of an interpretation in a local context. Controversy mainly arises over the question whether volumes and potential local consequences should be combined (LCA) or if they better be interpreted separately (WFA). Arguments for keeping them separate include:

- Volumes and potential local consequences remain explicit and transparent. Particularly in an agricultural water management context, water efficiency is a relevant parameter, which could be overlooked or hidden if inefficient WFs were to be multiplied by a low regional scarcity factor as would be the procedure in LCA (Vanham, 2023).
- Impact dimensions are still expressed in volumetric units, which means they retain a physical meaning (Hoekstra and Mekonnen, 2012).
- Different impact dimensions require different interventions to address them, so keeping them separate facilitates targeted action.

Arguments for combining them include:

- In complex supply chains with thousands of processes (e.g., electronics or automotive products), a disaggregated interpretation is hardly feasible – especially if water use is only one out of many impact categories.
- An impact-based WF allows for identifying local hotspots in complex global supply chains considering two relevant dimensions (volumes and local impacts), after which a more detailed analysis can and should follow.
- Even if dimensions are presented separately, they may be implicitly combined by users of results when they make decisions – the outcome depends on the qualification of users.

The different ways of performing the interpretation of water consumption volumes make both approaches suitable for specific questions users might want to answer. Guidance on use cases for the WFA and LCA approaches is provided in chapter 4.

2.2. Green water

2.2.1. Green water in WFA

Green water refers to the precipitation on land that does not run off or recharge the groundwater but is stored in the soil or temporarily stays on top of the soil or vegetation (Falkenmark, 2003; Hoekstra et al., 2011). Accordingly, the green WF refers to the consumption of green water resources. Green water consumption is particularly relevant for agricultural products through evaporation and transpiration during crop cultivation. Humanity consumes 6.5 times more green water compared to blue water (Hoekstra and Mekonnen, 2012), hence the early emphasis of WFA on the importance of including green water in WFA.

In terms of sustainability assessment, green water scarcity (GWS) and green water efficiency have been proposed as indicators. WFA quantifies GWS as the ratio of the green WF to its sustainably available level in a specific geographic area and time (e.g., Schyns et al., 2019). Maximum sustainably available green water can be estimated as the total available green water flow minus the green water flow to be reserved for nature. The latter can be estimated by considering the agroecological suitability and accessibility of land, biophysical limitations on land use intensification, and biodiversity conservation requirements (Schyns et al., 2019). GWS values exceeding a value of one indicate human overuse. WFA still lacks a comprehensive approach to determine green water requirements necessary to sustain biodiversity, primarily because biodiversity standards are spatially and temporally variable worldwide. In terms of green water efficiency, comparing green water consumption for a specific product across different locations helps to identify the best sites for water-efficient production. This can also be done within a single location using various management practices, evaluating site-specific water management and comparing regional suitability for crop growth. Poor local water management can be improved through water stewardship measures. Combining these measures with crop selection and improved agricultural management can optimize production systems, aiming for higher yields with less water. Moreover, in an agricultural context green water can be substituted by blue water, and the other way around, so that a complete picture can be obtained only by accounting for both (Hoekstra et al., 2011). Calculating the ratio of green to blue water consumption in irrigated agriculture, especially in areas with blue water scarcity, can further assist in the interpretation of blue and green WFs. A higher ratio indicates less relative pressure on blue water resources due to lower irrigation volumes.

2.2.2. Green water in LCA

The LCA community often neglects green water consumption because it is considered a consequence of land-use change whose resulting impacts are covered in other impact categories already. For example, the removal of ecosystems and the loss of biodiversity is assessed in dedicated land use impact assessment models (e.g., Koellner et al., 2013). Also, the impacts on soil health such as soil carbon sequestration or release, soil biodiversity, soil erosion and compaction under low green water availability can partially be assessed. An overview and discussion of impact assessment methods addressing these aspects is provided in section S1 in the supplementary material (SM).

Further, if green water is used inefficiently, the consequences are seen in reduced yields and/or in increased irrigation (blue) water consumption. While in theory many environmental consequences related to green water consumption may be addressed, in practice the current impact categories do not accurately cover all these impacts. This is because the description of soils and their changing water storage capacity under varying land use practices and intensities, and their temporal and spatial variation, is overly simplified in the covered impact categories (soil erosion, soil compaction). For this reason and because green water consumption is considered a relevant indicator, we call for a consideration of green water consumption in agricultural LCA studies.

In response to the criticism that natural ecosystems also consume green water (Hastings and Pegram, 2012) and considering LCA's goal of assessing environmental consequences, several authors suggested to analyze the difference in evapotranspiration resulting from an introduced land use compared to a reference (Hoekstra et al., 2011; Núñez et al., 2013; Quinteiro et al., 2015). Studies have shown that this so-called "net green WF" can even turn negative if the evapotranspiration of potential natural vegetation (PNV) is higher compared to that of current land use (Núñez et al., 2013; Quinteiro et al., 2015; Vanham and Bidoglio, 2013). In fact, historical land cover changes have reduced global green water fluxes to the atmosphere by an average of 7 % (Gerten et al., 2005).

Beyond the accounting level, an area is considered an environmental hotspot due to green water consumption when the product assessed affects the hydrological cycle (Núñez et al., 2018; Quinteiro et al., 2018) (i) by reducing runoff, thus impacting blue water availability for aquatic ecosystems and human water needs within a basin; (ii) by altering evaporation-to-precipitation recycling shares, decreasing rainfall for terrestrial ecosystems within the same or adjacent basins through atmospheric transport. Increased runoff after storms and excessive stream flows can also lead to environmental damage, although no method addresses these impacts yet.

2.2.3. Commonalities and differences

As a result of the discussion series, both LCA and WFA researchers agree that green WFs are useful indicators to measure the appropriation of water resources for human purposes and to quantify the water use efficiency of agricultural systems. In both approaches, green WFs do not fully capture environmental relevance, and further modelling is necessary to enable additional interpretation in terms of environmental impacts. WFA determines green WFs based on the claims human activities put on green water resources and evaluates these WFs based on local GWS and efficiency benchmarking. LCA calculates net green WFs and/or aims at modelling the effects of green water consumption and underlying land use change on the hydrological cycle comprising e.g. altered blue water availability or evaporation recycling via precipitation in the originating and other basins.

2.3. Water pollution

2.3.1. Grey WF in WFA

The grey WF is an indicator of water pollution associated with goods and services along their supply chains. It is defined as the hypothetical volume of freshwater required to assimilate pollution to the extent that ambient water quality standards are not violated. This definition should not be misinterpreted as a "dilution water requirement". In fact, the WF assessment manual (Hoekstra et al., 2011) specifically discourages the consideration of dilution as a solution to water pollution problems There can be situations in which the grey WF exceeds the actual water availability. Such cases where pollution surpasses the assimilation capacity exactly illustrate why the grey WF cannot be considered a "volume of water polluted", but is a volumetric indicator of water pollution. Grey WFs are calculated as the ratio of pollutant load to the maximum allowed concentration minus the natural background concentration of that same pollutant. When assessing multiple pollutants, the largest individual grey WF is defined as the overall grey WF, as this volume would also assimilate other pollutants sufficiently to meet their respective quality standards (Hoekstra et al., 2011). For diffuse pollution, the WFA manual suggests a three-tier accounting approach. The first tier prescribes using a pollutant fraction that reaches freshwater and is determined based on factors provided by the grey WF accounting and supporting guidelines. The second tier relies on standardized models, while the third tier requires use of sophisticated models (Franke et al., 2013).

To gain insight into the environmental sustainability of the grey WF, the water pollution level (WPL) was introduced as local impact indicator. By comparing the grey WF to available runoff (both specified in space and time), the WPL indicates pollution hotspots (Hoekstra et al., 2011; Liu et al., 2012).

Though the grey WF was developed to assess any pollutant, most research has been done on grey WFs of nitrogen and phosphorus (e.g., Mekonnen and Hoekstra, 2018, 2015). Recent grey WF case studies of other pollutants include pesticides (Vale et al., 2019; Yi et al., 2024) and pharmaceuticals (Wöhler et al., 2020).

2.3.2. Water pollution in LCA

Where WFA aims to indicate volumetric water needs required to assimilate water pollution by the ambient water system, LCA's main goal is to quantify potential environmental impacts resulting from the emission of pollutants, including eutrophication, acidification, human and ecotoxicity (e.g., Goedkoop et al., 2013). As a first step of assessing water pollution, pollutant loads and the environmental compartment receiving the emission are quantified in the life cycle inventory (LCI) analysis. This includes direct emissions (e.g. phosphate into freshwater or marine water) and indirect emission, such as SO_2 into air that eventually precipitates partly into freshwater, or pesticide emissions into agricultural soil that partly end up in groundwater. Like chemical water pollution, physical property changes of water, e.g. thermal loads from cooling water, are quantified in the LCI analysis (Raptis et al., 2017; Verones et al., 2010).

In the subsequent life cycle impact assessment (LCIA), the consequences of these emissions are quantified by means of standardized, (partially) mechanistic fate, exposure and effect models. For a chemical emission causing toxic impacts, this is done using the following modelling structure. For a unit emission, fate modelling estimates the chemical's mass increase in each environmental compartment including the chemical's residence time and mobility between compartments and over larger distances via advective transport mechanisms. The exposure model estimates how much of this mass is taken in by a population (human or ecosystem), and the effect models quantify the resulting toxic effects expected in this population expressed in e.g. toxicity potentials (Rosenbaum et al., 2008). As described in the section on blue water consumption above, this so-called midpoint impact assessment can further be complemented by endpoint methods which model damages on ecosystems (measured as the potentially disappeared fraction of species) and human health (quantified as Disability-Adjusted Life Years (DALYs)) (Goedkoop et al., 2013). For non-chemical pollution (e.g. thermal pollution), the same step is adopted for the assessment of their potential impacts on aquatic ecosystems. In LCIA, comprehensive modelling of (water) pollution impacts is necessary to reflect the main drivers which are 1) emitted pollutant and load quantity; 2) environmental persistence; 3) mobility; 4) exposure potential; and 5) harmful effects. The higher a pollutant's potential in each of these aspects, the larger its potential impact (and CF).

A typical LCA study contains several hundreds, sometimes thousands, of potentially harmful pollutants (usually emitted at different locations and moments during a product's life cycle). However, more than 99 % of human toxicity and ecotoxicity impacts are usually caused by 10 to 15 pollutants (much less for eutrophying or acidifying emissions), while the remaining hundreds (or thousands) contribute (far) less than 1 % to toxic pollution impacts. This allows to prioritize and focus on these few problematic emissions, which is useful from a decision support perspective, justifying the comprehensive modelling.

Beyond its consideration in human health and ecosystem quality, the relevance of water quality degradation for the assessment of the availability of freshwater as a natural resource has also been explored. For example, Pradinaud and colleagues (2019) suggested using the concept of recovery period to distinguish when water degradation affects human health or ecosystems (short-term impacts, recovery period below e.g. 100 years), or the future availability of water as a resource (long-term impacts, recovery period above e.g. 100 years).

2.3.3. Commonalities and differences

The first difference between the two approaches lies in their development history. While LCA started with methods addressing water pollution, WFA started with assessing blue and green water consumption. This historical background is still reflected in how the methods are applied: LCA studies almost always consider water pollution but sometimes neglect water consumption. Vice versa, WFA studies typically focus on blue and green water consumption but often scope out the grey WF component.

The main difference between the two approaches is their way of measuring water pollution either by means of (hypothetical) volumes of water needed to assimilate pollutants (WFA) or by means of various water-related impact categories (LCA).

Another difference can be found in the spatial perspective of the assessment model. The grey WF focusses on a river basin context using (local) natural background concentrations as well as maximum allowable concentrations, frequently based on legal standards which differ geographically. While spatially explicit impact assessment methods for water pollution exist in LCA for freshwater eutrophication and aquatic acidification as well (e.g. Ortiz-Reyes and Anex, 2018; Seppälä et al., 2006; Zhou et al., 2024), commonly applied toxicity methods take an averaged, continental perspective (e.g., Goedkoop et al., 2013; Rosenbaum et al., 2008).

With regard to spatio-temporal pollution accounting, both WFA and LCA include emissions to air and soil ending up in freshwater. However, LCA considers the residence time during the environmental passage (from emission over (sub)basins to oceans), the altered pollution concentrations along this passage, and the resulting impacts in down-stream (sub)basins. In contrast, the grey WF considers effects of pollutants in the receiving water body only. This choice originates from two reasons: i) it makes the estimation of water pollution relatively simple; and ii) water quality may improve over the course of a natural water flow and it is considered not plausible to take potentially changed water quality downstream as an indicator for water quality impacts at the location where the pollutant enters the water system. If it was exactly known which pollution fraction first enters ground- and surface water, respectively, two separate grey WFs could be calculated (Hoekstra et al., 2011).

Another distinction between grey WF and LCA is how they account for a diversity of pollutants ending up in the same water body. As mentioned above, the grey WF is defined as the one resulting from the most penalizing pollutant, arguing that if this pollutant can be assimilated the others can be too. This is justified considering the conceptual definition but sometimes perceived as counterintuitive because a reduction in the emission of other pollutants would not change the grey WF result. If the concept is misunderstood, this might limit the incentive to reduce other emissions than the most penalizing one in a water management context. In contrast, because of its focus on assessing impacts, LCA quantifies the potential consequences on human health or ecosystems which result from different pollutants. Moreover, in LCA a pollution impact is generally considered marginal compared to other pollution of the same substance in a watershed. Hence, water pollution impacts per unit assessed (e.g. per product produced) do not change the reference situation and therefore have no influence on the CF (see also section 2.1). However, more recently scholars have argued to replace this approach with an average impact accounting where the change in reference situation is accounted for (Heijungs, 2021; Huijbregts et al., 2011).

Both methods currently cannot depict the effects of pollutant mixtures, which can be higher or lower than the sum of their individual components. This is not just a methodological shortcoming, but a consequence of the currently limited understanding of pollutant mixtures' environmental behaviour, and the non-availability of thresholds (WFA) and impact assessment factors (LCA) for pollutant mixtures. An additional modelling problem is that fate modelling would have to determine whether or not any subset or combination of hundreds of chemicals emitted all over the planet into different compartments and at different moments in time actually "meet" each other in the environment in order to mix and interact.

2.4. General commonalities and differences across all three water types

Next to the specific discussions on green and blue water consumption and on water pollution, the following overarching commonalities and differences between the two methods can be observed. Before discussing methodological differences, it should be noted that already the terminology used in both approaches can differ – even concerning basic terms like water footprint, water scarcity, or water availability. A detailed comparison can be found in the supplementary material (SM).

The main difference between WFA and LCA observed in all three "water colours" is their respective focus on volumes (WFA) and potential impacts (LCA). This explains the explicit inclusion of green WFs in WFA and LCA's consideration of net green WFs and consequences on the hydrological cycle. It also explains why volumetric footprints and local scarcity are analyzed separately in WFA and why they are eventually combined to water scarcity footprints (WSF) in LCA. Also concerning water pollution, the different emphasis explains the calculation of a volumetric grey WF in WFA and multiple freshwater impacts in LCA.

Both approaches agree on the relevance of volumetric consumption and resulting local consequences. However, in practice WFA studies often report green, blue, and grey WFs only and lack a local contextualization – even though the WFA manual explicitly prescribes following up accounting with a sustainability assessment (Hoekstra et al., 2011). Likewise, LCA studies often focus on impacts only and neglect analyzing consumption and pollution on the inventory level – even though ISO 14044 requires an interpretation on both LCI and LCIA level.

Another consequence of the emphasis on either volumes or impacts can be seen in the way in which water consumption and pollution are combined. In WFA, the consumption of green and blue water volumes is directly compared to (or aggregated with) the volumetric grey WF. While this allows for easily understandable and communicable results of a product's freshwater appropriation, this aggregation is also criticized because: i) the grey WF denotes a hypothetical and not a physical volume of water (needed to assimilate pollutants); ii) in practice also polluted water is used and consumed; and iii) an aggregation implies equal importance (and substitutability) of the three water types. In LCA, impacts of water consumption and pollution are evaluated separately. When endpoint impact assessment models are applied, results can directly be compared and aggregated – even to non-water-related environmental interferences such as GHG emissions.

Further, considering the communities in which the methods have been developed, the LCA approach has mainly been applied to industrial and agricultural product systems, whereas WFA has a focus on agricultural production as it is the largest water user by a margin. In terms of the level of analysis, WFA initially focused on the total production of crops or the total water use in basins, and LCA typically assessed water use of individual products. However, with an increasing application of LCA to also organizations and regions (Loiseau et al., 2022; Martínez-Blanco et al., 2015) and with a growing interest in WFA of products, companies, and consumers (Hoekstra, 2017), the scopes of both approaches are increasingly overlapping.

Regarding applicability, LCA can make use of existing LCI databases (which contain water consumption and pollutant emissions per product/process), applicable impact assessment methods, and LCA software applications (which combine the two). In WFA, due to its region-specific focus, water consumption and water pollution figures are often determined in each study individually to calculate the blue, green, and grey WF.

3. Case study

3.1. Introduction

This section presents a WF study of a sofa using the LCA and WFA approaches. The following subsections show the specific methods and data used to determine green and blue water consumption and pollution, results obtained by means of LCA and WFA, as well as a discussion and conclusion section on the practical implications of the methodological differences.

3.2. Methods and data

As the purpose of this case study is to illustrate the differences between LCA and WFA and not to achieve the most precise results, the analysis considered the production phase only (cradle-to-gate) and focused on the production of the materials while neglecting transports, the manufacturing of the sofa, and packaging. The material composition shown in Table 1 is based on an existing environmental product declaration of a real sofa (EPD, 2020) to which the study added a cotton cover to have renewable and non-renewable raw materials represented in the product system.

Data for water consumption and water pollution were derived from the ecoinvent 3.9.1 database (ecoinvent, 2023) and the product system was modelled in the GaBi software (Sphera, 2023) as shown in Fig. S1 in the SM. For cotton, green and blue water consumption from irrigation were adopted from a recently released global crop WF dataset (Mialyk et al., 2024). This dataset gives the most recent information and allows for spatial disaggregation because it provides grid-cell and country-specific water consumption data. As it is not known from where cotton is purchased, sourcing according to global production shares was assumed. To determine a global average water consumption of cotton, the study weighted the country-specific green and blue water consumption volumes of the top 11 producing countries (averaged for the period 2015–2019 and representing 90 % of global production as shown in Table S1) according to their production shares.

The following subsections present the methods for determining green and blue water consumption as well as water pollution by means of LCA and WFA.

3.2.1. Blue water assessment methods

In LCA, blue water consumption is calculated by subtracting water discharges from blue water withdrawals listed in the ecoinvent datasets of the non-renewable materials. For cotton, blue water consumption is directly listed in the dataset of Mialyk et al. (2024). To allow for an assessment of local impacts, the location of water consumption needs to be known. For cotton, the producing countries and their production shares can be derived from the dataset directly. For the non-renewable materials, spatial information is available in the ecoinvent datasets. However, a large share of water consumption originates from underlying processes which are classified as Rest of Europe (RER) or Rest of the World (RoW). To allow for a more precise assessment, the study allocated water consumption volumes of the individual materials to specific countries based on the water consumption distribution in a specific water inventory database (WELLE, 2020). A WSF was determined by multiplying the regionalized blue water inventory by country-specific mid-point characterization factors (CFs) derived from the AWARE

Table 1
Material composition of the sofa and global (GLO) datasets used to determine water consumption and pollution.

Material	Weight [kg]	Dataset used
Aluminium	25.000	market for aluminium, wrought alloy (GLO)
Steel	0.174	market for steel, low-alloyed (GLO)
Rubber	0.070	market for synthetic rubber (GLO)
Polypropylene	0.800	market for polypropylene, granulate (GLO)
Polyurethane	5.750	market for polyurethane, flexible foam, flame retardant (GLO)
Cotton	1.000	market for fibre, cotton (GLO), water consumption from (Mialyk et al., 2024)

model (Boulay et al., 2018). Even though AWARE and other impact assessment methods provide characterization factors, also at the basin level and in monthly resolution, an assessment at the country level is common in LCA because the LCA databases contain water consumption figures at this level only. However, in this case study, the dataset of Mialyk et al. (2024) does provide the water consumption of cotton at the grid cell level as well (Fig. S2). To reveal the differences to a country level assessment, the study recalculated the WSF of cotton produced in China at the basin scale.

In contrast to LCA, which is often used to determine environmental impacts according to global production mixes, WFA typically analyses a specific water-related question, in a specific supply situation, in a specific region. For this purpose, it either measures, models or derives volumes of blue water consumption from (crop-)specific WF databases. Presupposing the accuracy of LCA databases, in this case study WFA used the same method and data to determine the volumetric blue WF of the sofa. However, as mentioned in chapter 2, WFA rejects the idea of combined water scarcity footprints and instead interprets the volumes of local blue water consumption figures based on local scarcity and efficiency at the spatial resolution of river basins. This information is not available in LCA databases, and it would be an immense task considering a sofa consisting of six materials, of which each is produced in numerous countries and in even more river basins. Therefore, the WFA approach for analyzing the environmental sustainability is illustrated by applying it to cotton sourced from China only. For efficiency, the Chinese top 50 % benchmark of 181 m^3/t (only blue water) for irrigated cotton production was used. To determine water scarcity in Chinese basins, the study applied a ratio of total blue water consumption over availability minus environmental flow requirements and a threshold for significant water scarcity of 1.5 (Mekonnen and Hoekstra, 2016).

3.2.2. Green water assessment methods

The only material of the sofa causing green water consumption is cotton. LCA uses the net green WF to indicate the difference between cotton's green water consumption and evapotranspiration of PNV, which has been determined on the country-level based on the data provided by Nunez et al. (2013).

By means of the method of Link et al. (2020), the influence of the net green WF to remote basins via reprecipitation is assessed. This is exemplarily applied to cotton production in China and includes an analysis of how cotton production and the resulting change in land cover and evaporation in China's drainage basins leads to changes in precipitation in remote catchments. Gridded values on evaporation from a PNV are extracted from the outputs of dynamic vegetation modeling (Schaphoff et al., 2018; Von Bloh et al., 2018) and are aggregated to basin scales. The net green WF per basin is determined via the difference to cotton's "gross" green WFs while additionally considering the harvest area and growth period in each basin for a fair comparison (Mialyk et al., 2024). As LCA often considers green water consumption as a consequence of land-use change, the study calculated the land needed to produce 1 kg of cotton under rainfed and irrigated scenarios using yield response factors (Steduto et al., 2012). Further, to assess the impacts of green water consumption on soil quality and the hydrological cycle, the indicators soil erosion, water purification (soil capacity to clean the water), infiltration, and groundwater regeneration were assessed using the LANCA v2.5 method (De Laurentiis et al., 2019). LANCA stands for land use indicator value Calculation and these indicators were applied for the assessment to the country level with inventory data for the evaporation from a PNV extracted from Nunez et al. (2013).

For WFA, the study used the gross green WF determined based on the global average production shares as described above. To illustrate the sustainability assessment of these volumes, the study compared green water consumption of only rainfed cotton production in different Chinese basins to the corresponding national top 50 % benchmark of 1,229 m^3/t (only green water) determined based on the dataset of Mialyk et al. (2024). For analyzing green water consumption in relation to green water scarcity, the study used the level of green water appropriation determined by Schyns et al.(2019) and set the threshold to 85 %. It should be noted that the WFA approach only requires an interpretation of the green WFs – the way of implementation was selected by the authors of this paper and can vary between studies.

3.2.3. Water pollution assessment methods

For LCA, based on the material composition of the sofa and the ecoinvent datasets, the emissions of pollutants to freshwater were determined on the life cycle inventory (LCI) level. The study used these emissions to calculate the LCA results in the impact categories freshwater eutrophication, ecotoxicity, and acidification by multiplying them with the characterization factors provided by the Environmental Footprint 3.1 method (EF 3.1, 2022) (excluding long-term emissions). For WFA, the emissions contributing most to the LCA results (antimony, arsenic, chromium + VI, phosphorous, pyrene, and zinc) were selected to calculate the grey WF.

3.3. Results

3.3.1. Blue water in LCA

The total blue water consumption of the sofa is 5,316 L. While the sofa's material composition is dominated by aluminium (Fig. 2a), blue water consumption is mainly caused by cotton (46 %), aluminium (40 %), and polyurethane (Fig. 2b). Results show a WSF of 172.7 m^3 world-equivalents, which can be interpreted as the equivalent quantity of water consumed in a global average water scarcity situation. Even though cotton represents 3 % of the sofa's bill of materials only, it is responsible for 71 % of its WSF.

Fig. 3 shows that water consumption takes place in 39 countries (grey-shaded countries), with the top 10 countries representing 93 % of the water consumption (blue bars). Most water consumption takes place in China as it represents relevant production shares of cotton, aluminium, and polyurethan. Comparing the country-specific contribution, the water consumption in China is dominating the result of both volumetric blue water consumption and the WSF. In contrast, the water consumption in Pakistan, Turkmenistan, and Uzbekistan doubles its contribution to the share of the WSF due to local scarcity. Vice versa, water consumption in water-abundant regions like Russia or Germany reduces their share in the WSF.

When recalculating the WSF for Chinese cotton production at the basin scale (Fig. S2), the WSF increases by 10 % (from 32.7 to 36.0 m^3 world-equivalents) because cotton is grown in basins with a water scarcity above the Chinese average.

3.3.2. Blue water in WFA

The volumetric blue WF equals the one determined in LCA (5,316 L) with the same contribution of materials (Fig. 2) and regional distribution (Fig. 3a). Assessing the environmental sustainability of the water consumption of cotton produced in China, results shown in Table 2 reveal that half (51 %) of the cotton production uses water efficiently (below the top 50 % benchmark of 181 m^3/t). However, less than 1 % of Chinese cotton is produced in non-water scarce basins (WS index below 1.5), which renders more than 99 % of Chinese cotton production unsustainable.

3.3.3. Green water in LCA

The net green WF of the sofa is 555 L, which indicates that the production of the cotton cover causes 555 L more water consumption than PNV in the cotton cultivation areas. Only Mexico and Turkmenistan have negative net green WFs, indicating that the PNV in those regions would cause higher evapotranspiration than cotton fields. Fig. 4 shows the regional distribution of the net green WF.

Analyzing the links between water consumption and land use, Fig. 5a shows that cotton production in dominantly irrigated croplands in Turkmenistan requires five times less land than within rainfed croplands

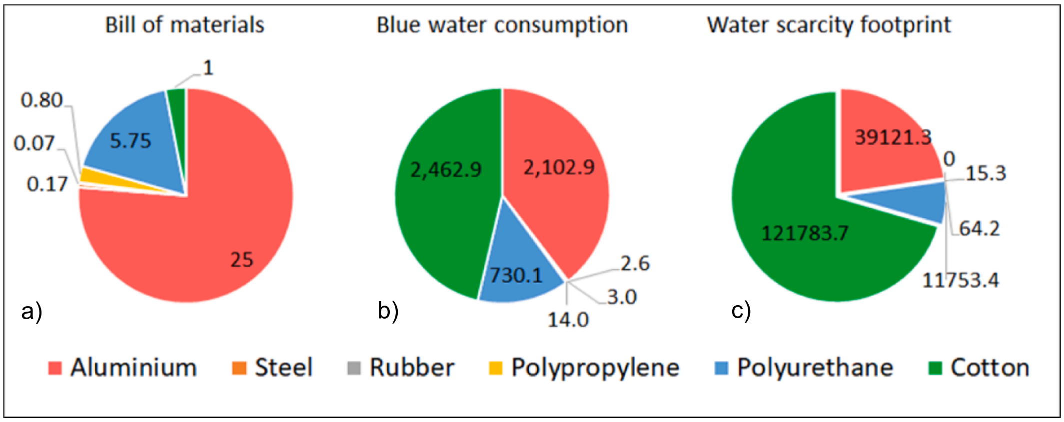

Fig. 2. Shares of materials in the sofa's mass [kg] (a), blue water consumption [L] (b), and water scarcity footprint [L world-equivalent] (c). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(0.7 ha t^{-1} versus 3.6 ha t^{-1}). However, in Brazil and Turkey, where cotton hardly needs irrigation, land requirements are almost the same with or without irrigation. Overall, the use of land and irrigation water is inversely related, which illustrates the need for a combined environmental assessment.

Fig. 5b-e shows the impacts of the land use change (and green water consumption) on soil erosion, water purification (soil capacity to clean the water), infiltration, and groundwater recharge. Impacts in China, as the leading country in the global cotton production market, are relatively low. Erosions and groundwater regeneration impacts are the highest in India, the second largest contributor to global cotton production. This indicates that using cotton from other producing countries might be better to reduce the assessed list of land use-related impacts.

Table 3 shows the results of net green water and its effects on the recycling of atmospheric moisture on a basin level considering China. Except for the Hong (Red River), the Gobi Interior, and the South China Sea Coast basins, net evaporation is positive meaning that there is a surplus of green water evaporation discharge to the atmosphere due to cotton production. However, effective net green water consumption (Net GWCeff) is often significantly different due to high fractions of basin internal evaporation recycling (BIER) (see, e.g., the Yangtze basin where one quarter of the water evaporated rains back in the same drainage basin). Besides evaporation being recycled internally, some basins show huge fractions of basin external evaporation recycling (BEER) leading to high shares of moisture being recycled over land. In this context, the right column of Table 3 shows to what extent cotton production can lead to water gains in remote basins of the Earth due to bridges of atmospheric moisture. Considering the production shares in the respective basins, the results indicate that, on average, cotton-related net green water consumption leads to external water gains in remote basins of about 205 m^3/t of cotton produced. Nevertheless, such statements are inadequate for evaluating potential benefits, and more detailed information on the fate of evaporation and the site conditions of water-receiving basins is required. Fig. S3 illustrates an alternative approach to the presentation of results, focusing on plotting the core regions of average reprecipitation on a grid cell level from a sample basin (Yangtze basin). Such an analysis could serve as a starting point for further investigation, which could incorporate a more detailed localized analysis of the effects of runoff and green water resources for the originating and receiving basins.

3.3.4. Green water in WFA

The green water footprint of the 1 kg cotton cover of the sofa is 4,060 L, and Fig. 6 shows its regional distribution.

Analyzing these numbers, Fig. 7 shows the green and net green WFs (m^3 per ha) in cotton-producing countries as well as the share of green water in the total WF. In areas like Brazil, where cotton is primarily rainfed, the green WFs per hectare are high, negating the need for irrigation, and conversely low in primarily irrigated areas like Uzbekistan and Turkmenistan.

The analysis of the environmental sustainability of the green water consumption of cotton produced in China (Table 4) reveals that half (44 %) of the cotton production uses water efficiently (below the top 50 % benchmark of 1,229 m^3/t). However, only 20 % of Chinese cotton is produced in basins which do not exceed a green water appropriation level of 85 %. In combination, ca. 80 % of the green water consumption of Chinese cotton production is considered unsustainable.

3.3.5. Water pollution in LCA

As a result of the life cycle inventory (LCI) analysis, Fig. 8 shows a selection of relevant emissions with phosphorus emissions dominating the results, followed by chromium and arsenic.

The results of the subsequent life cycle impact assessment (LCIA) and the contributions of individual materials to the impact categories are shown in Fig. 9. In line with the material composition of the sofa, aluminium also contributes most to freshwater eutrophication and acidification. In contrast, ecotoxicity is dominated by the contribution of polyurethane. Contributions of the other materials are relatively small. From a substance perspective, results for acidification are dominated by emissions of SO_2 to air (ending up in water and soil) while eutrophication results are dominated by phosphate emissions to freshwater and ecotoxicity is mainly influenced by the emissions of inorganic substances to freshwater (Fig. S4).

3.3.6. Grey WF in WFA

The grey WF was calculated based on the different emissions shown in Fig. 8. The individual grey WFs range from 1 m^3 (antimony) to 2,514 m^3 (chromium + VI) and are largely driven by the sofa's aluminium components (Fig. 10). As the largest volume allows for assimilating the other emissions as well, 2.541 m^3 denotes the overall grey WF of the sofa.

3.4. Discussion

After showing the results of blue and green water consumption and of water pollution obtained by the WFA and LCA approaches, this section compares them to each other and discusses the methodological implications.

3.4.1. Blue water

As the case study used the same method and data, both LCA and WFA show the same volumetric WF with the same spatial distribution (Fig. 3a). As discussed in chapter 2, the main difference is the interpretation of the volumetric blue water consumption, which is either

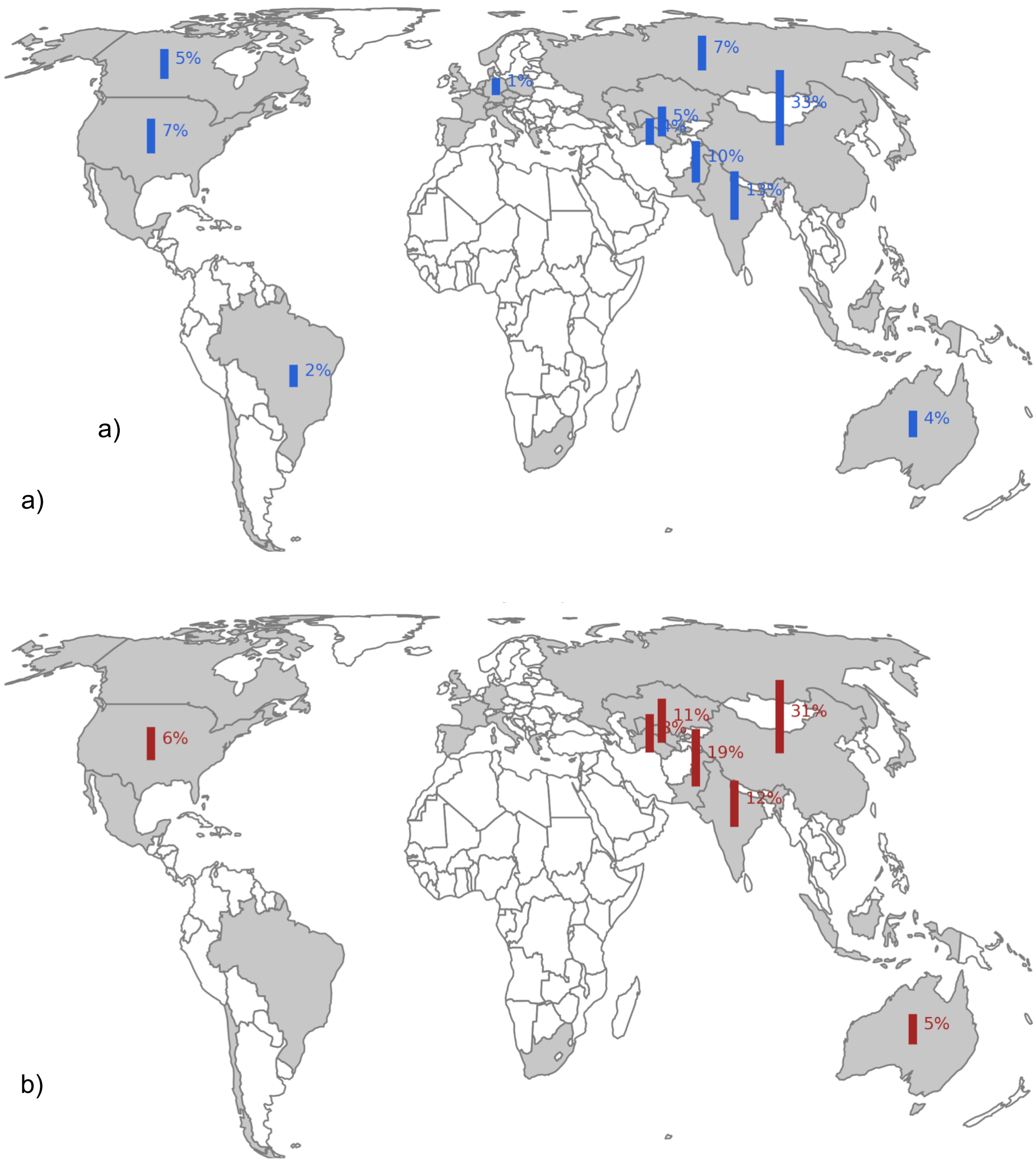

Fig. 3. Regional distribution of the sofa's blue water consumption (a) and water scarcity footprint as determined by AWARE (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Basin-specific blue water consumption of irrigated Chinese cotton production and assessment of environmental sustainability based on efficiency (50 % benchmark 181 m^3/t) and water scarcity (threshold 1.5). Green is desirable, and red is undesirable.

Basin name	Production share	Unit blue WF m^3/t	Efficient	Water scarcity index	Water scarce	Sustainable
Huang He	8 %	194.5	No	7.9	Yes	No
Tarim Interior	21 %	1082.8	No	18.1	Yes	No
Hong (Red River)	0 %	31.1	Yes	0.0	No	Yes
Yangtze	25 %	66.4	Yes	1.8	Yes	No
Gobi Interior	10 %	1049.1	No	12.3	Yes	No
Xun Jiang	0 %	45.6	Yes	0.2	No	Yes
China Coast	26 %	108.3	Yes	6.0	Yes	No
Bo Hai – Korean Bay, North Coast	0 %	201.2	No	7.0	Yes	No
Ziya He, Interior	7 %	208.9	No	28.3	Yes	No
Lake Balkash	1 %	613.4	No	2.5	Yes	No
China, mainland	100 %	459.2	No	14.9	Yes	No

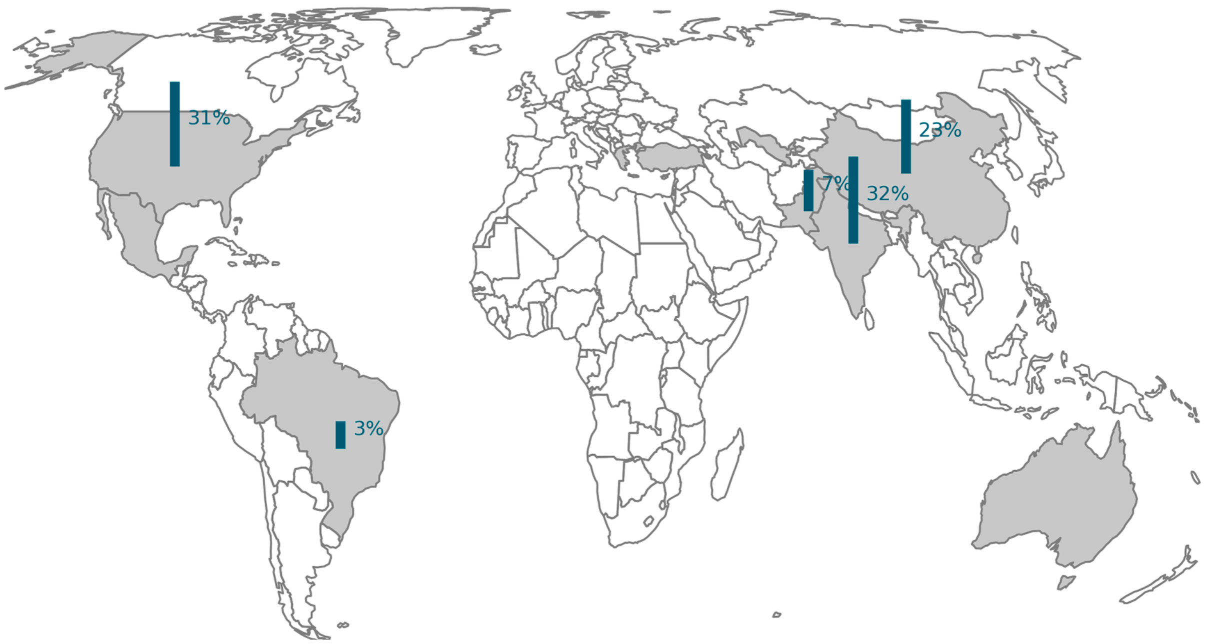

Fig. 4. Regional distribution of the sofa's net green water consumption. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

accomplished by putting it in the context of local scarcity and efficiency in WFA or by means of combined WSF in LCA. The criticism of the WSF that it combines the dimensions of consumption and scarcity and, thus, loses transparency (Vanham, 2023) could be validated in this case study. Indeed, a separate assessment of cotton grown in specific basins in China has provided relevant information on efficiency and scarcity. However, it was also shown that already a simple product like a sofa (consisting of six materials only) resulted in water consumption in 39 countries and hundreds of basins. For this reason, the separate assessment could only be demonstrated for one material (cotton) in one country (China). Hence, such an approach is hardly feasible if products with complex supply chains are analyzed and if the WF is one out of many impact categories only.

A main challenge for LCA is that the assessment in this case study and in general is typically done at the country level even though the hydrological situation can vary significantly – especially in large countries like China. While the impact assessment methods provide characterization factors (CFs) at the basin level and in monthly resolution, the LCI datasets currently provide water consumption figures at the country level only. This shortcoming is partly reduced by means of consumption-weighted average CFs. That is, the basins and months in which a large share of the country's water consumption occurs, also influence the country's CF stronger. Nevertheless, the case study revealed that the WSF determined on the basin level is 10 % larger than the one determined based on the country's average AWARE factor. This seems acceptable because the intention of LCA is to identify blue water-related hotspots concerning materials (cotton) and countries (China, India, Pakistan) according to which optimization strategies can be derived. WSF results can also be the starting point for a more detailed analysis at local hotspots in global supply chains to e.g. invest in measures increasing the blue water efficiency.

3.4.2. Green water

In contrast to the sofa's green WF of 4,060 L analyzed in WFA, the net green WF of 555 L obtained in LCA is significantly lower and denotes the additional evaporation compared to PNV. Both, WFA's green and LCA's net green WFs are dominated by China, India, and the US. In contrast, cotton production in China was not relevant for the impact assessment results, which were driven by land use changes in India, Pakistan and Turkmenistan. Further, LCA additionally analyzed the fate of the net green WFs, revealing additional re-precipitation in the originating and neighbouring basins. Even though the methods to assess volumetric footprints in both approaches look different, both rely on land use information: while the assessment in LCA is based on land use directly, WFA uses indicators such as the level of green water appropriation, which is influenced by land use patterns.

3.4.3. Water pollution

When comparing the results of LCA and WFA, both approaches indicate that the use of aluminium in the sofa contributes most to the environmental impact categories freshwater eutrophication and acidification (LCA) and the grey WF resulting from various emissions (WFA). Especially the contribution of materials to the grey WF resulting from phosphorous is identical to the contribution of materials to freshwater eutrophication because it is dominated by the emission of phosphorous. In contrast, the result of the impact category ecotoxicity is dominated by the emissions resulting from the production of polyurethane, which does not play a relevant role in grey WFs. In general, the analysis of the sofa's freshwater pollution by means of different impact categories in LCA reveals a more comprehensive result while the grey WF provides a single and intuitive result allowing for comparison to water consumption figures.

4. Recommendations

Based on the methodological comparison in chapter 2 and the findings of the case study in chapter 3, application-dependent recommendations for analyzing blue and green water consumption as well as water pollution are developed. For this, the strengths and weaknesses of WFA and LCA in relation to specific questions which decision-makers may have are discussed to show the individual strengths of both approaches. Moreover, recommendations for future research that could jointly be addressed by the WFA and LCA communities are provided.

4.1. Recommendations for blue water

Relevant questions that decision-makers may have regarding blue water consumption as well as the strengths and weaknesses of

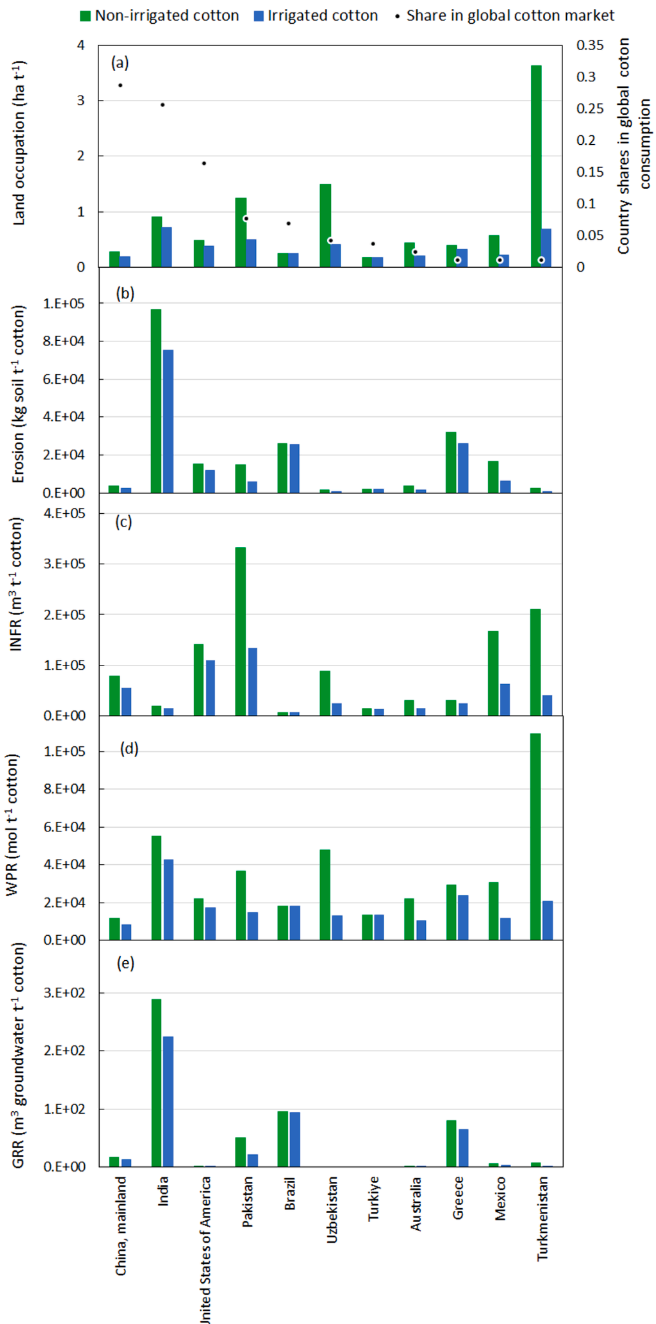

Fig. 5. Comparison of land use and land use-related impacts for cotton production under rainfed and irrigated conditions for largest global producers. a) land occupation; b) erosion; c) infiltration reduction (INFR); d) water purification reduction (WPR); e) groundwater regeneration reduction (GRR).

volumetric and impact-based metrics in relation to these questions are shown in Table 5. In summary, volumetric indexes denoting blue water consumption (blue WF or LCI) are recommended for questions about freshwater appropriation and water efficiency.

Questions related to freshwater deprivation and to identifying hotspots can be answered by both metrics. Volumetric indicators are more transparent as dimensions of volumes, scarcity, and efficiency are analyzed separately, which makes them particularly useful in the analysis of agricultural production systems and for water management. However, as shown in the case study, they are challenging to apply if complex supply chains are involved. Vice versa, impact-based metrics combine relevant dimensions which loses transparency but makes them useful for the analysis of complex product systems in which water is only one of many environmental dimensions. To increase transparency, LCA studies should not only report LCIA results but also evaluate water consumption separately.

Questions related to the relevance of blue water consumption in comparison to water pollution can be analyzed by both approaches either on the volumetric level (WFA) or on the (endpoint) impact level (LCA). Additionally, endpoint models are recommended for assessing specific impact pathways on human health and biodiversity and for comparisons of blue water consumption to non-water related impacts.

Table 3
Basin-specific net green water consumption (Net GWC) of Chinese cotton production and fractions of evaporated water per basin reprecipitating in the originating basin (BIER:), across the sum of all external basins (BEER) and overall, over land (TER). The effective Net GWC (Net GWCeff) denotes consumption minus the fraction of water reprecipitating back in the originating basin; basin external water gains due to bridges of atmospheric moisture represent the product of Net GWC and BEER; recycling ratios for China are determined by production weighted averages.

Basin_name	Net GWC in m^3 / t	BIER	BEER	TER	Net GWC_{eff} in m^3 / t	Basin external water gains in m^3 / t
Amur	1042.5	0.230	0.304	0.534	802.7	316.9
Huang He	577.6	0.122	0.462	0.584	507.1	266.8
Hong (Red River)	−142.2	0.065	0.580	0.645	−132.9	−82.5
Yangtze	512.8	0.244	0.337	0.581	387.7	172.8
Mekong	162.2	0.085	0.718	0.802	148.5	116.5
Gobi Interior	−19714.5	0.081	0.540	0.620	−18117.6	−10645.8
Xun Jiang	65.7	0.097	0.457	0.554	59.3	30.0
China Coast	186.0	0.069	0.310	0.379	173.1	57.7
Bo Hai – Korean Bay, North Coast	582.1	0.049	0.427	0.476	553.5	248.5
Ziya He, Interior	626.2	0.056	0.432	0.488	591.2	270.5
South China Sea Coast	−144.4	0.022	0.459	0.482	−141.3	−66.3
Salween	197.6	0.091	0.688	0.779	179.7	136.0
China, mainland	528.4	0.091	0.389	0.480	480.1	205.4

4.2. Recommendations for green water

Table 6 summarizes relevant questions that the decision-makers may have concerning the consumption of green water, along with strengths and weaknesses of the WFA and LCA approaches in relation to them. As can be seen, the approaches have been designed to answer quite different questions. For questions related to freshwater appropriation, water efficiency, the sustainability of green water consumption, and crop selection, the green WF concept proposed by WFA is recommended. It is particularly useful for local applications such as agricultural water management, crop selection, or water allocation. LCA is recommended for analyzing changed green water consumption in comparison to PNV, i.e. net green water, the resulting consequences on the hydrological cycle, and the land use change underlying green water consumption. It is especially useful for assessing water-land related impacts of product systems with complex supply chains.

4.3. Recommendations to assess water pollution

Table 7 lists relevant questions that decision-makers may have regarding water pollution as well as the strengths and weaknesses of the grey WF and LCA impact categories. Both approaches can quantify water

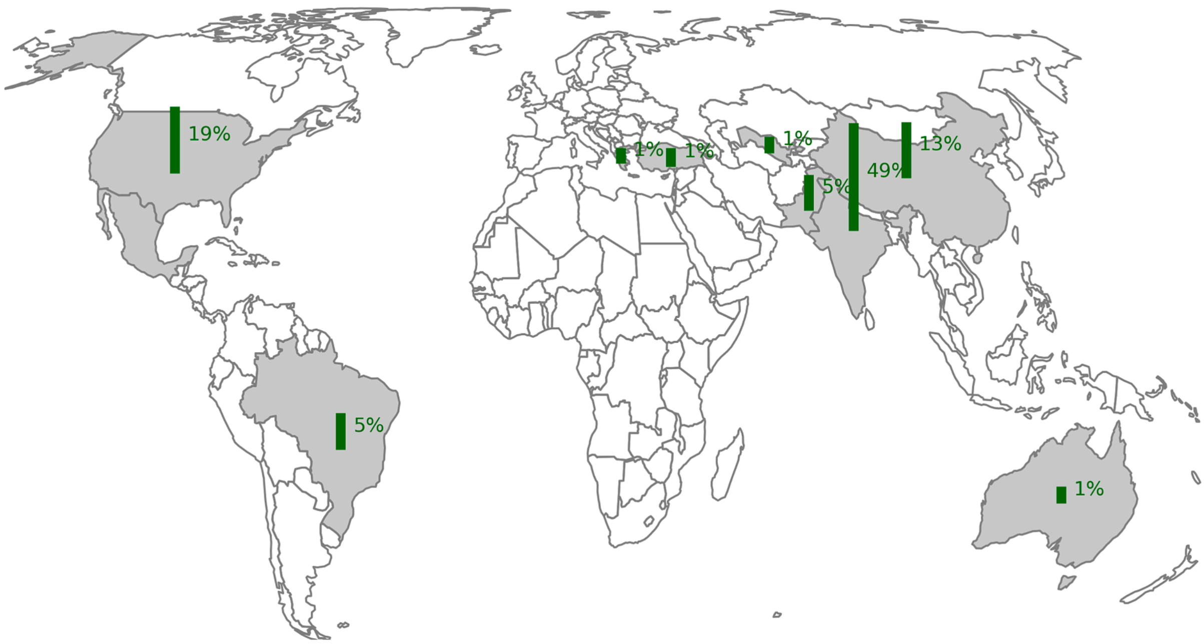

Fig. 6. Regional distribution of the sofa's green water consumption. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

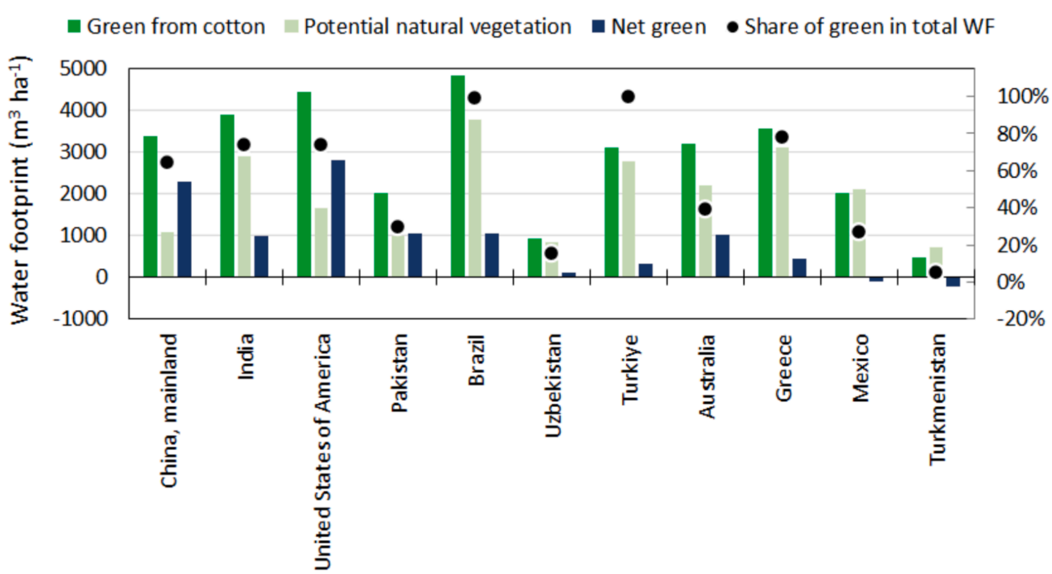

Fig. 7. Comparison of the green WF of cotton production and of potential natural vegetation for the largest global producers averaged for the 2015–2019 period. Note that WF is expressed in m3 ha-1 in order to compare to natural vegetation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

pollution and identify regional, sectoral, or process/product-related hotspots as well as individual pollutants driving the results. Further, both approaches enable comparing water pollution to water consumption. The modelling of explicit impact pathways makes LCA impact categories particularly suitable for answering questions related to environmental consequences of pollution and for comparing water pollution to other environmental interferences. Together with strengths in operationalization, this makes LCA impact categories strong for questions related to the management/reduction of water pollution in complex production systems characterized by multiple pollutants. However, results are more complex, more difficult to communicate, and include uncertainties. The grey WF especially shows its strength when taking a watershed-based perspective by elucidating spatially explicitly to what extent the assimilation capacity of water bodies has been used.

4.4. Recommendations for future research

During the online discussions and the process of writing this paper, several research ideas have been collected which are summarized in this section.

1) With regard to blue water consumption, WFA and LCA typically focus on not having enough water. However, none of the models currently address the challenge of having excessive water. Hence, it could be discussed if this aspect should be considered in the scope of WF. If so, methods to analyze the causes and impacts of flooding or

Table 4
Basin-specific green water consumption of rainfed Chinese cotton production and assessment of environmental sustainability based on efficiency (50 % benchmark 1,229 m^3/t) and green water appropriation (threshold 85 %). Green is desirable, and red is undesirable.

Basin_name	Production share	Unit green WF m^3/t	Efficient	Level of green water appropriation	Water scarce	Sustainable
Amur	0 %	1837.8	No	61 %	No	No
Huang He	3 %	1094.0	Yes	78 %	No	Yes
Hong (Red River)	0 %	637.9	Yes	45 %	No	Yes
Yangtze	16 %	1012.6	Yes	64 %	No	Yes
Mekong	0 %	634.0	Yes	43 %	No	Yes
Gobi Interior	0 %	5511.5	No	35 %	No	No
Xun Jiang	1 %	837.5	Yes	52 %	No	Yes
China Coast	24 %	834.4	Yes	87 %	Yes	No
Bo Hai – Korean Bay, North Coast	1 %	1143.7	Yes	72 %	No	Yes
Ziya He, Interior	56 %	1286.8	No	90 %	Yes	No
South China Sea Coast	0 %	853.4	Yes	57 %	No	Yes
Salween	0 %	672.7	Yes	46 %	No	Yes
China, mainland	100 %	1082.9	Yes	85 %	No	Yes

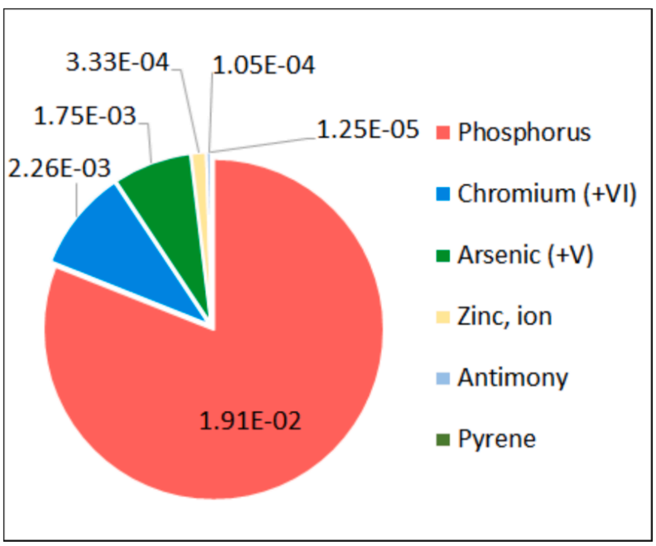

Fig. 8. Load of Phosphorus, Chromium (+VI), Arsenic (+V), Zinc (ion), Antimony and Pyrene (kg) to freshwater resulting from the sofa production.

water logging could be developed. Further, impacts of reduced freshwater flows into marine coastal waters on e.g. marine habitats, sedimentation, and coastal human activities is not considered in current assessment schemes and should be explored in future research.

2) Regarding green water, the quantification of absolute sustainability has been identified as a research challenge. Recent studies suggested to consi soil moisture as the local and global planetary boundary for green water. There are dry and wet green water boundaries based on pre-industrial soil moisture levels for each location. However, next to green water consumption, factors such as land use, climate change, and groundwater levels affect soil moisture. Thus, it could be investigated how green water consumption alone influences whether an area stays within or exceeds its green water planetary boundary.
3) Further, the role of rainwater harvesting in analyzing WFs should be clarified. Rainwater is typically perceived as being available "for free" and often not considered in water accounting. However, if the rainwater had not been collected, a part of it would have evaporated and the other part would have become surface runoff or groundwater recharge. It can thus be argued that it makes little difference if the rainwater is collected and used directly or if is used after being stored in a water body. To model rainwater harvesting more consistently, an accounting framework which considered the reference state and the fractions of rainwater becoming direct evaporation, green water, and blue water should be developed.
4) Another shortcoming identified is the current approach of considering blue and green water in isolation, even though green water consumption can influence blue water availability and vice versa. For this reason, multi-media fate models are proposed (Núñez et al., 2018). Such models have only recently been operationalized in the work of Pierrat and colleagues (2023b). They estimate the consequences of blue water consumption and land use change on the global hydrological cycle in different environmental compartments (water, land, atmosphere) and should be applied and enhanced in the future.

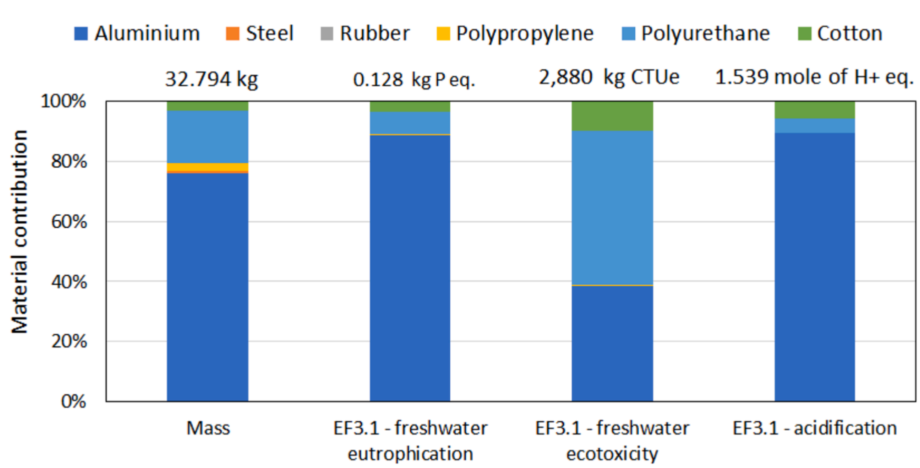

Fig. 9. LCIA results of the sofa in water pollution impact categories and contribution of materials to these results (in comparison to mass composition).

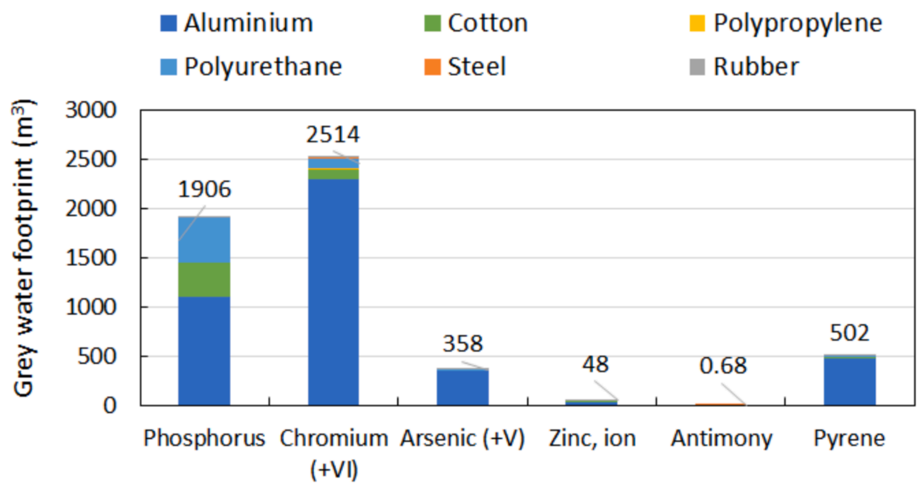

Fig. 10. Grey WFs determined based on different pollutants and materials causing their emission.

Table 5
Questions related to blue water consumption and the advantages/disadvantages of volumetric and impact-based metrics.

Question	Volumetric metrics (m^3 / unit or units/m^3)		Impact-based metrics (WSF or endpoint-result/unit)	
	Strengths	Weaknesses	Strengths	Weaknesses
What is a product's, company's, or consumer's appropriation of (blue) freshwater?	Indicator directly answers question and easy to understand & communicate.	None.	Not designed for this question.	Not designed for this question (would add unnecessary complexity).
Which option uses (blue) water more efficiently?	Indicator directly answers question and easy to understand & communicate.	None.	Not designed for this question.	Combination of volumes and scarcity can hide/ favor inefficient uses in water-abundant areas.
Which product causes more/ less freshwater deprivation for other users?	If volumes are related to local scarcity, transparent assessment of two relevant dimensions.	Separate consideration of consumption and scarcity is challenging in complex supply chains.	Combines volumetric consumption and local scarcity/impacts in one metric, and thus facilitates decision-making based on both aspects.	Lacking transparency because volumes and scarcity get mixed. Guidance needed for the choice between marginal and average CFs.
Which product causes smaller impacts on biodiversity or human health (resulting from water consumption)?	Implicitly considered in water scarcity analysis, which contains environmental requirements and can serve as proxy for human health.	No consideration of cause-effect chains linking water consumption and biodiversity or human health.	Indicator directly answers question. Combines volumetric consumption and local impact pathways, and thus facilitates decision-making based on both aspects.	Multiple relevant impact dimensions get mixed, which lacks transparency. Uncertainty in endpoint modelling.
Where in the supply chain are water-related hotspots?	Multiple types of hotspots can be defined and identified, e.g. large volumes, inefficiencies, scarcity. Easy to communicate.	Separate consideration of different hotspots is challenging in complex supply chains.	Combines volumetric consumption and local scarcity/impacts in one metric. This facilitates identifying hotspots based on several aspects – especially in complex supply chains.	Multiple relevant impact dimensions get mixed which lacks transparency.
How relevant is water consumption in comparison to water pollution?	Same unit as grey WF allows for comparison and aggregation.	Can overestimate total freshwater appropriation as polluted water can still be used for low-quality applications. Same units imply comparability and substitutability of green, blue and grey water, which may not be the case.	Endpoint characterization models allow for comparing impacts of consumption and pollution on human health, biodiversity, and resources.	Uncertainty in endpoint modelling (comparison at the level of orders of magnitude).
How relevant are impacts caused by water consumption in comparison to non-water impacts (GHG emissions, land use, etc.)	Not designed for this question. Can be combined with other footprints to show trade-offs	Not designed for this question. Cannot be compared directly with other footprints due to different units.	Endpoint indicators directly answer question. Endpoint characterization models allow for comparing water- and non-water-related impacts on human health, biodiversity, and resources	Uncertainty in endpoint modelling (comparison at the level of orders of magnitude).

5) Regarding water quality, current methods in WFA and LCA focus on assessing chemical and physical water quality degradation. However, biological aspects, such as pathogenic pollution or invasive species are typically neglected. First methodological approaches integrate risk assessment indicators for pathogenic pollution into LCIA methods (Bhatt et al., 2023; Heimersson et al., 2014) or use proxies such as percentage of invasive species (Schenck, 2001). Given the relevance of biological pollution, a more detailed assessment in the scope of WFA and LCA is recommended.
6) Finally, we suggest that the WFA and LCA communities make use of the knowledge created in the respective other community. For example, LCI databases could incorporate data on the blue and green WFs of crops, which have currently been developed in high spatial resolution and at global scope (e.g., Mialyk et al., 2024). Vice versa,

Table 6
Questions related to green water consumption and the advantages/disadvantages of WFA and LCA.

Question	Green WF Strengths	Weaknesses	LCA Strengths	Weaknesses
What is the total green water appropriation of a system? Which option uses (green) water more efficiently?	Green WF indicator directly answers these question and is easy to understand and communicate.	None for this question. But additional interpretation is needed.	Not designed for this question, but evapotranspiration can be derived from some LCA databases as an inventory indicator.	Not designed for this question
How sustainable are the green WFs?	In interpretation step, green WFs are compared to benchmarks and scarcity, allowing for a transparent assessment.	Challenging to apply in complex supply chains.	Not designed for this question. LCA rather analyzes underlying land-use change and effects on the hydrological cycle	Not designed for this question
Which crops should be selected considering green water availability?	Green WFs can be compared to green water availability to assess suitability and irrigation demands	None.	Not designed for this question	Not designed for this question
What is the green water appropriation in comparison to PNV?	Not designed for this question	Not designed for this question	Net green WF used in LCA is designed to answer this question.	Needs detailed knowledge of the natural ecosystem for indicator development, which is hard to obtain.
What are the local or global impacts of this net green WF?	Not designed for this question.	Not designed for this question.	Consequences of the alterations of green water flows are considered in (a) soil-surface water interface by altering natural runoff, and (b) soil-atmosphere interface by changing evaporation. Associated impacts of these alterations are considered as, for example, erosion and flooding under (a), and drought intensification through soil moisture alteration under (b).	Not designed to predict the impacts of water consumption on the specific contemporary situation.
What are the environmental impacts of the underlying land use change?	Not designed for this question.	Not designed for this question.	Land use indicators directly answer question and are easily applicable.	Uncertainties in impact assessment models and challenging in communication.

water consumption and emission data of industrial processes derived from LCI databases can be used in modelling the blue and grey WFs of background systems in crop WFA studies (e.g., production of machinery, fuels, fertilizers). Further, LCIA fate models could be implemented in the grey WF method to support the operationalization of tier 2 and 3 grey WF models (Mekonnen and Hoekstra, 2011) that aim at analyzing how many pollutants end up in water bodies.

5. Conclusions

To increase mutual understanding and pave the way for a constructive cooperation, researchers from the WFA and LCA communities have engaged in a two-year discussion series to: i) explain their ways of assessing water consumption and pollution; ii) apply both approaches in a case study; and iii) develop application-dependent recommendations.

Concerning blue water (ground and surface water), both approaches start with quantifying the volumes of water consumed and add an interpretation to address the sustainability of consumption in a local context. While WFA focuses on analyzing the efficiency of water consumption and on relating WF accounts to local scarcity, LCA multiplies local water consumption by a characterization factor to derive impact-based WFs. In terms of green water (precipitation), WFA determines green WFs (evapotranspiration) and contextualizes them by means of local green water scarcity and efficiency benchmarking. The LCA approach calculates net green WFs (difference in evapotranspiration compared to natural vegetation) and aims at modelling the effects of green water consumption and the underlying land use changes on the hydrological cycle comprising e.g. altered blue water availability or evaporation recycling. Regarding water pollution, WFA calculates hypothetical volumes of water needed to assimilate pollutants until quality standards are reached (grey WF). LCA assesses impacts of multiple pollutants in various impact categories, such as freshwater eutrophication, aquatic acidification, and freshwater eco-toxicity.

The case study revealed that both approaches come to similar findings concerning volumetric blue water consumption, relevant freshwater pollutants, and the materials driving the results. However, the different approaches in interpreting green and net green water consumption have partly led to the identification of different local hotspots. Further, LCA's impact assessment models have identified SO_2 emissions to air as a relevant driver for water-related impacts concerning acidification. The study has also shown that both WFA and LCA can make use of databases developed by the "other" community.

Our recommendations indicate that both approaches are applicable to various products, sectors, and scales. WFA has its strengths in questions related to freshwater appropriation and region-specific analyses considering water allocation, efficiency and scarcity, making it particularly useful for crop selection as well as agricultural and river basin water management. With its focus on environmental impacts, LCA is strong in assessing consequences of water use on other users and in comparison to broader environmental impacts – especially if complex supply chains are involved. Rather than being in competition with each other, both approaches have individual strengths that enable addressing the world's water challenges in a complementary way.

CRediT authorship contribution statement

Markus Berger: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Winnie Gerbens-Leenes:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Fatemeh Karandish:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Maite M. Aldaya:** Writing – original draft, Investigation. **Anne-Marie Boulay:** Writing – original draft, Investigation. **Rick J. Hogeboom:** Writing – original draft, Investigation. **Andreas Link:** Writing – original draft, Investigation, Formal analysis. **Alessandro Manzardo:** Writing – original draft, Investigation. **Oleksandr Mialyk:** Writing – original draft, Visualization, Investigation, Formal analysis. **Masaharu Motoshita:** Writing – original draft, Investigation. **Montserrat Nuñez:** Writing – original draft, Investigation, Formal analysis. **Stephan Pfister:** Writing – original draft, Investigation. **Ralph K. Rosenbaum:** Writing – original

Table 7
Questions related to water pollution and the advantages/disadvantages of the grey WF and LCA.

Question	Grey WF		LCA impact categories	
	Strengths	Weaknesses	Strengths	Weaknesses
How large is the water pollution?	Indicator directly answers the question. Directly communicable to the general public.	Complex (and no common practice yet) for product supply chains with diverse emissions in different catchments.	Indicator directly answers this question. Specifies the potential impacts of each pollutant. Includes many pollutants of the assessed system. Considers direct and indirect (via soil or air pollution transfer) freshwater pollution as well as pollution transport between watersheds.	The results are not directly communicable to the general public, but need to be processed or explained.
What are the environmental consequences of pollution?	Next to emissions, also the water body's assimilation capacity is considered	If the ambient water quality standards are political targets, the maximum allowed concentrations do not necessarily relate to environmental consequences.	Indicator directly answers this question. Assesses the potential impacts of many freshwater (and other) pollutants on human health and ecosystems, distinguishing regional differences and the influence of the place of emission.	Complexity of different impact category results. Uncertainties in complex characterization models.
How important is water pollution relative to consumptive use?	Indicator was developed to directly compare degradative to consumptive water use	Implies equal relevance of grey and blue/green WFs. Potential overestimation if polluted water can still be used for certain consumptive purposes.	Endpoint methods are designed to address these questions by quantifying health and ecosystem damages resulting from water consumption, water pollution and other environmental interferences.	Uncertainties in endpoint models. Methods enabling the comparison of "apples and oranges" are difficult to explain and understand.
How important is water pollution relative to other environmental consequences?	Indicator not designed for this question.	Indicator not designed for this question.		
What are pollution hotspots (in terms of region, process, sector, product)?	For processes, sectors and products, their GWFs (or for regions the corresponding WPLs) can be compared in order to identify hotspots	None.	Pollution hotspots can be identified and their causes (in terms of region, process, sector, product) ranked based on their contribution to environmental consequences.	None.
What are the most relevant pollutants?	Different substances causing different problems can be considered in one unit based on legal limits.	All pollutants have to be assessed individually (currently without pre-existing databases or software).	Can identify and rank the most environmentally relevant pollutants (out of hundreds or thousands present in a typical LCA study) in terms of their potential impact on human health and ecosystem quality/biodiversity.	Inherent uncertainty will allow to identify the 10–15 most relevant pollutants out of hundreds or thousands, but does usually not allow to reliably rank these. In consequence, any of these 10–15 substances might be THE most relevant one.
How is future water availability affected?	The GWF can indicate to what extent pollution has to reduce to not exceed the water body's assimilation capacity	Long-term emissions and impacts are (currently) not considered. A method to use GWF for forecasts/projections has not yet been established	Long-term emissions and impacts are considered (although frequently omitted by practitioners). Future needs and options for technologies compensating for limited water availability can be identified and modelled.	Assessing future availability of clean water still requires further method development.
How to reduce water pollution of a product, company, or region?	Supports understanding what effect pollution reduction has compared to reducing water consumption	Reducing the grey WF (of the most polluting substance(s)) does not guarantee good environmental practice and reduction of other pollutants does not influence the result.	Relevant pollutants and processes can be identified and ranked according to reduction potential (assuming highest impact = highest reduction potential).	None.
What is the level of operationalization?	Only three inputs are required for each pollutant to estimate GWFs (pollutant load, natural background concentration, maximum allowed concentration)	Methods to calculate input data for GWF estimations have to be developed for pollutants that have not been studied before. For non-frequently studied pollutants, obtaining input data is labour- and time-intensive	A screening LCA study with secondary data can be done in a few hours to a few days. Very cost-efficient apart from primary data acquisition.	Large degree of freedom for modelling choices (needed for the wide range of LCA applications) requires experience to correctly use LCA methodology and interpret its results. Primary data acquisition is labour- and time-intensive.

draft, Investigation. **Laura Scherer:** Writing – original draft, Investigation. **Han Su:** Writing – original draft, Investigation. **Lara Wöhler:** Writing – original draft, Methodology, Investigation, Formal analysis.

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.

Acknowledgements

The authors thank Dr Lauren Seaby Anderson from the Potsdam Institute for Climate Research for providing data on evaporation from potential natural vegetation used for the case study in this paper. The authors from IRTA appreciate the financial support of the CERCA program (Generalitat de Catalunya), and the financial support of AGAUR (Generalitat de Catalunya) to the Consolidated Research Group "Sustainability in Biosystems" (no. ref. 2021 SGR 01568). Montserrat Nuñez thanks the Ramon y Cajal grant (RYC 2020) funded by the Spanish

Ministry of Science and Innovation and the European Social Fund, "ESF Investing in your future". Fatemeh Karandish would like to thank the financial support from European Union (ERC Starting Grant, GROW-101041110.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2025.113458.

Data availability

No data was used for the research described in the article.

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