Agri-food corporations' role in water sustainability and water resilience of global supply chains

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Abstract: Agriculture is both a major contributor to water scarcity and highly vulnerable to it. The agri-food sector accounts for approximately 70% of global human water abstraction and 90% of water consumption, with irrigation practices leading to detrimental effects such as reduced streamflow, groundwater depletion, and environmental degradation. As water stress impacts crop and livestock productivity, exacerbated by climate change, the sector faces increasing water-related risks. While much research focuses on food production, little attention has been given to the intermediaries in the food supply chain, which can significantly influence water outcomes. This review explores the role of agri-food trading corporations in shaping water sustainability and resilience within food systems.

Agri-food corporations occupy a critical position in the food supply chain, connecting farmers to consumers, yet their influence on water use is often overlooked. These corporations — including transnational commodity traders like ADM, Bunge, Cargill, and Louis-Dreyfus (the "ABCDs") - control vast portions of the global food market, thereby influencing water usage patterns through sourcing practices, commercial decisions, and supply chain management. Unlike farmers, whose numbers are vast, and consumers, whose demands are widespread, corporations are fewer in number but wield significant control over resource allocation and production choices, including water use.

Despite this influence of transnational trading corporations (TNCs), current metrics for assessing the water risks and sustainability of food supply chains are often inadequate and lack the robustness needed for transparent decision-making. A comprehensive approach that includes intermediaries in water risk assessments, alongside farmers and consumers, is essential for improving water outcomes. To address these challenges, agri-food corporations must integrate water risks into their business models, set clear, measurable targets for water usage and ensure greater transparency throughout the supply chain. This review argues that the path to a water-secure world requires transforming corporate strategies to prioritize water sustainability,

thereby fostering innovation, resilience, and long-term growth. Achieving such transformation requires concerted efforts across all levels of the food system, ensuring that water risks are adequately accounted for and managed and sustainable practices are mainstreamed throughout global food production.

1. Introduction

Agriculture is both *responsible for* and *vulnerable to* water scarcity, which occurs when demand for water exceeds its supply. The agri-food sector draws about 70% of all human water abstraction globally, and accounts for 90% of all human water consumption (indeed, water used by crops evaporates rather than flowing back to the local watershed after use). Human activities overexploit water resources in many water basins across the world, and 4 billion people live in regions experiencing water stress for at least one month each year (Mekonnen and Hoekstra, 2016). In particular, irrigation leads to reduced streamflow (Vorosmarty C.J. et al. 2000, Falkenmark and Rockstrom, 2005; Scanlon B.R. et al. 2007) and groundwater depletion (Wada et al. 2010, Dalin et al. 2017, Tuninetti et al. 2019), with harmful consequences for water quality, aquatic biodiversity, geophysical and biological functioning and drinking water supply. In these cases, agri-food production is unsustainable as it relies on a resource that is not renewed as fast as it is consumed. Crop and livestock productivity has already suffered from increased water stress, as well as from water-related extremes (droughts and floods; e.g. McCarthy et al 2021), which are expected to worsen under future climate change. Given its high dependence on water, the agri-food sector is particularly vulnerable to these increased water risks. This paper discusses opportunities to reduce water risks and improve water sustainability in the agri-food sector by focusing on transnational trading corporations and other intermediary actors. Though much attention has been given to food producers and consumers, we argue that agri-food transnational corporations (TNCs) can serve as a pivot within the food supply chain, shaping both consumer demand and preferences, as well as food production at the farm-field level.

Food systems research, especially that which focuses on environmental impacts of food systems, overwhelmingly addresses the production-side and farm-stage of the supply chain - rather than all stages from input manufacturing (e.g. fertilisers) to household consumption and waste (Davis et al., 2021; Read et al., 2020). Studies also look at the retail and consumer side, but often, the set of actors in the food supply chain that connects final consumers to the water resources impacts occurring on farmland - or the ‘missing middle’ (Falloon et al., 2022) - is not explicitly considered. We argue that these actors and TNCs are key because they are much less numerous than farmers (~0.1 billion) and consumers (~8 billion), while also significantly influencing the water outcomes of food systems through their upstream supply chain sourcing and commercial decisions. While there are more than six hundred million farms globally (Lowder et al., 2021), there are a relatively small number of governments, financial institutions (e.g., banks and insurance corporations), and agri-food TNCs that strongly shape farmers’ decision-making, including water use on farms. Through subsidies, quotas, and other policies (either directly or indirectly related to food and water), governments significantly influence what crops are grown, and on where and how they are grown. Likewise, insurance corporations and government-sponsored insurance schemes lower the costs of production and sometimes cause greater water use. For example, India provides subsidised energy for irrigation water pumping (e.g., Badiani et al., 2012; Fishman et al., 2016) and the USA subsidise crop insurance (Sanderson and Huges 2019). Finally, only a handful of TNCs control a large part of all food sold globally. Based on supermarket sales data in the USA, four firms or fewer controlled at least 50% of the market for 79% of the groceries (Lakhani et al., 2021). These TNCs significantly shape consumer demand and set prices and standards for farmers. This market concentration has significantly increased in the past four decades (Lakhani et al., 2021).

Regarding agricultural commodity-trading firms, the four dominant firms - known as the ABCDs (ADM, Bunge, Cargill and Louis-Dreyfus) - control together over 70% of the global food market (UNCTAD 2023) and 90% of the grain market (Oxfam, 2012). Thus, they influence prices, access to funding, and directly participate in financial markets (UNCTAD, 2023). They are key players in the countries exporting wheat, soybean, maize, rice and palm oil, which are Argentina, Australia, Brazil, Canada, China, Indonesia, Malaysia, Russia and the USA (see Figure 1: water resources embedded in countries' imports compared to the water resources embedded in trade by a single agri-food corporation). These firms operate as networked TNCs, extending their global reach through networks of independent contract manufacturers (Bartley et al., 2018).

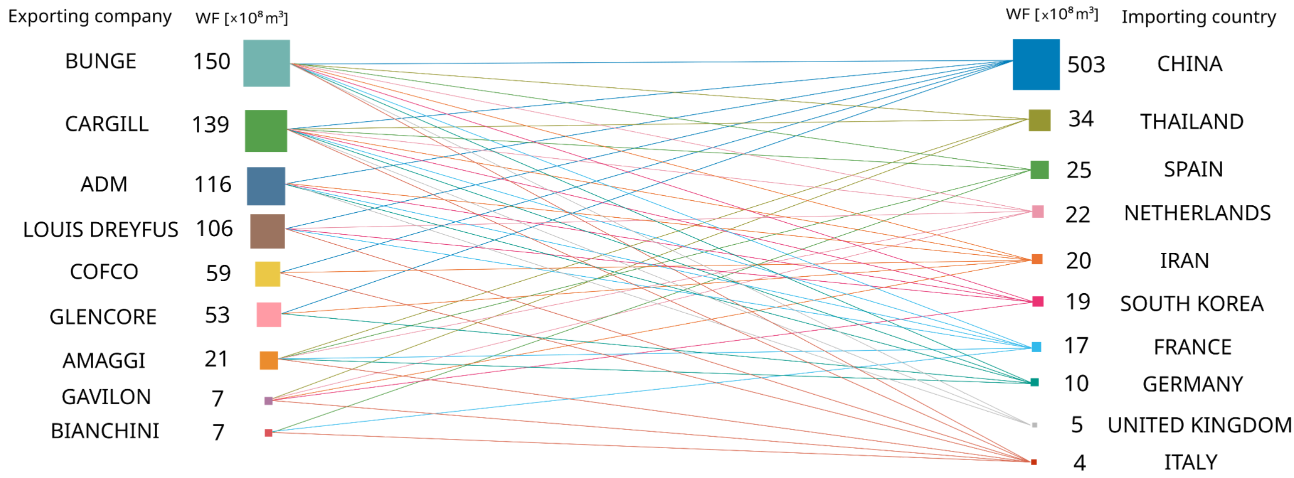

Figure 1 : Soybean exports from Brazil: virtual water trade volumes (amount of water consumed to grow traded soybean) for the top-ten importing countries in 2018, through the handling of dominant corporations. The virtual water volume imported by these ten countries via these nine corporations accounts for 70 % of the total water volume embedded in Brazilian soy exports.
Source: De Petrillo et al., 2023

Since these actors are already shaping farmer behaviour, as well as consumer demand, a complementary approach to trying to move food systems to a more sustainable state by informing/changing the actions of millions of *farmers*, could be to work through the more concentrated actors (i.e., agri-food *TNCs*, banks, governments) to coordinate efforts and develop a consistent set of goals and corresponding metrics. Transparency, clarity of goals, metrics, and actions, as well as an alignment or balancing of interests between stakeholders are key to achieving water resilience and sustainability.

The complex interplay between water resources and the agri-food sector requires a comprehensive approach to risk assessment and management. Current assessments of water risks by agri-food TNCs often focus primarily on blue water (irrigation water from surface reservoirs, rivers and groundwater) consumption and availability. While these are crucial aspects, they fail to capture the full spectrum of risks that corporations and stakeholders face. Other significant water-related risk categories across agri-food TNCs' operations and supply chain that require attention include regulatory, reputational and transition risks, failure or degradation of critical water infrastructure, degraded water quality, green water (soil water replenished by rainfall) scarcity, flood hazards, water transport challenges, and reputational risks. Water hazards have been and are likely to remain a significant risk facing corporations, such as through flooded rivers that disrupt transport of key commodities, as occurred on the Mississippi River in 2019, or river transport disruptions due to drought, such as on the Danube River or Yangtze River in the summer of 2022. Even without considering these broader water-related risks, food, beverage, and agriculture corporations surveyed by the CDP said that the maximal financial impact of the water risks they assessed was nearly eighteen times greater than the costs to proactively address these risks (CDP, 2020). In other words, while the costs of inaction to mitigate these risks far exceeds that of action, there is a persistent and widespread lack of corporate adoption of tools to assess and track water risk and sustainability.

We argue that there is a significant potential to reduce water risks and improve water sustainability in the agri-food sector by introducing evidence-based principles in business and governmental decisions. This requires combining environmental and economic data to be able to trace the sustainability and risk to foods along global supply chains, and for actors to use verified data and common metrics. The sustainability, risks, and costs associated with agri-food corporate water use must be carefully considered and weighted to maximize co-benefits and mitigate trade-offs. While the regular and real-time measurement and tracking of these multiple objectives of corporate supply chain water use can inform such considerations, such quantifications are currently lacking.
Indeed, there is a lack of data collection and transparency in agri-food business, which prevents both informed consumer decision-making and effective business strategy with respect to water. Crucially, TNCs currently rely on diversification of supply to protect themselves from scarcity-related risks, rather than taking a longer-term approach by sourcing more resilient and/or less impactful products and/or by helping suppliers adopt water-resilient farming methods. Therefore, an analysis of water risk should first clarify what that risk specifically entails (e.g., a physical water shortage, a drop in production, a damage to infrastructure, or losses for the environment) and who is affected (e.g., corporations, consumers, or the water system and the environment). Most companies adopt an inward-facing view of water risk, concentrating on impacts that hydrological changes could have on their system of production. Conversely, hydrologists look at water risk in the context of impacts on the water system (e.g., droughts, floods or depletion of freshwater reserves). The objective of this paper is to review current data and practices around water-related risks and sustainability of water use in agri-food supply chains, and to suggest how food supply chain corporations could improve consideration of water to improve both resilience to water-related risks and sustainability of agricultural water use worldwide.

2. Potential of science & data to estimate water risk and water sustainability of agri-food corporations

TNCs that trade crucial crops - such as wheat, corn, soy, cotton, and palm oil - can be key drivers for change (Schneider et al. 2020) and for stewardship initiatives. Examples of stewardship initiatives exist for the ocean (Virdin et al., 2021) the biosphere (Rockstrom 2021), and carbon emissions (Escobar et al., 2020). Regarding water, the concepts of virtual water content, water footprint and virtual water trade could be used in decisions to enhance the effectiveness of supply-chain policies and help meet global sustainable targets, as suggested in (Godar et al. 2016, Flach et al. 2016, Croft et al. 2018). The concept of virtual water content was introduced by Allan (2003), who suggested that virtual water import, i.e., the water resources embedded in imported goods, was a mechanism that contributed to compensate for water shortages in Middle Eastern countries. The private sector's influence on global water governance has been underlined (Bartley et al. 2018, Rudebeck et al. 2019, Grabs & Carodenuto 2021), and the virtual water concept can help connect producers, traders, retailers, importers and consumers to local water resources. Indeed, this concept allows us to identify connections, dependencies and vulnerabilities within global food trade by connecting state-of-the-art water sustainability and risk assessment to the whole supply chain. The link via virtual water can be applied to combine a metric considering the chosen water sustainability indicator at the farm level and trade flows at different retailing stages.

A crucial metric used in the literature to explore the nexus between food production and water consumption, is the Water Footprint (WF) (Hoekstra et al. 2011). The WF measures the water use related to goods and services produced or consumed by an individual (or a country), separating green water (contributed by precipitation water stored in the soil) from blue water (surface and groundwater used for irrigation). When applied to agricultural goods, the WF is often evaluated per unit of product/crop, in order to provide a measure of the volume of water consumed and thus measured in cubic meters of water per ton of edible harvested crop (unit WF). At the production or farm level, a product's WF can be evaluated through farmer measurements, remote sensing, or crop modeling (Mekonnen & Hoekstra, 2011, Tuninetti et al., 2015, Chiarelli et al., 2020, Mialyk et al., 2024) (Table 1). While the blue WF measures direct consumption from surface and groundwater resources (Mekonnen & Hoekstra, 2011), it does not capture the social or ecological impacts on local communities or the sustainability of future resources; this requires additional impact analyses. Incorporating green WF metrics, which assess consumption of precipitation-derived water within soil for crop growth (Mekonnen & Hoekstra, 2011), enriches this evaluation (Wang-Erlandsson et al. 2018, Wang-Erlandsson et al., 2022), especially under climate change and land-use transformations (He & Rosa, 2023).

This framework requires a sub-national analysis of trade (Pandit et al., 2023) in order to connect the specific production location of agricultural commodities with the network of the actors involved in the supply chain (producers, processors, sellers and buyers). It also requires spatial mapping methodologies designed to improve traceability and accountability within the supply chain (Godar et al., 2016). Indeed, the emblematic example of Brazilian soy sub-national virtual water trade (De Petrillo et al., 2023) leverages the Spatial Explicit Information on Production to Consumption Systems (SEI-PCS), first introduced by Godar et al. (2015).
De Petrillo et al. (2023) applied the virtual water concept as a tool to quantify the water consumption associated with soy trade by TNCs to importing countries. Examples of unit WF assessment linked to trading corporations and importing corporations through virtual water trade are shown for Brazilian soy in Figures 2 and 3, where the total WF at the municipality scale of production and the total virtual water export associated with trading corporations are connected to first-importing countries.

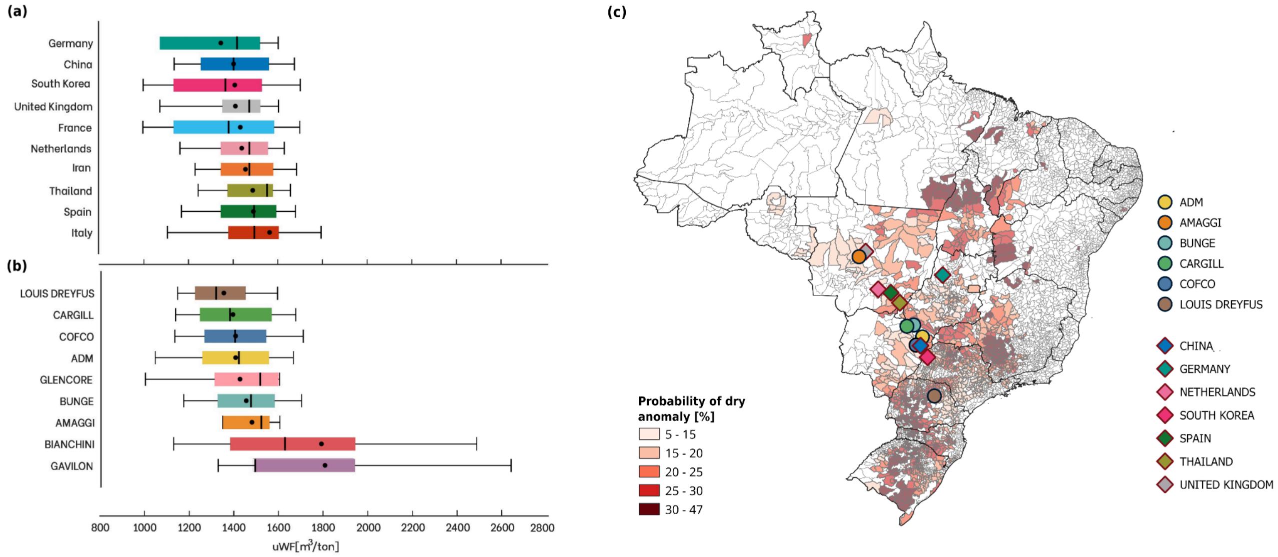

Figure 2. Boxplots of the unit water footprint (m^3/ton) of soybean production, where each dot represents the value for a producing municipality of Brazil, for **(a)** the top-ten importing countries in 2018 and **(b)** the top-nine trading corporations. The left and the right whiskers refer to 10th- and 90th-percentile, respectively, the black dot represents the average and black line the median unit WF.
(c) Average location from where corporations (colored circles) and countries (colored diamonds) import Brazilian soybean, based on where the soy correspond to highest virtual water trade flows; and exposure to droughts, in probability of occurrence of a dry anomaly (red background shade) in soy producing municipalities in 2018. Key importing countries, ABCD and COFCO trading corporations are shown. Adapted from De Petrillo et al., 2023.

Figure 2 shows the heterogeneous unit WF across Brazil for ten largest soy importing countries and nine TNCs of soy in 2018. The unit WF of importing countries shows smaller variability compared to that of TNCs: from a minimum of 1340 m3/ton (Germany) to a maximum of 1560 m3/ton (Italy) versus 1350 m3/ton (Louis Dreyfus) to 1800 m3/ton (Gavilon). Hence, importers can average out their *unit WF* thanks to their ability to source from a heterogeneous basket of corporations displacing their business activity across the Brazilian country.

The average soy sourcing location of TNCs –weighted by their annual water footprint volumes– in Figure 2 (panel c) show that virtual water flows originate from climatically and agronomically heterogeneous sites over Brazilian biomes, from the transition Amazon-Cerrado to Pampa, passing through Pantanal and Mata Atlantica. This strong sub-national heterogeneity means that soy producers - and thus corporations and importing countries - can have very different water footprints. Similarly, the drought probability means these actors have different drought risk exposures (defined here as the occurrence of a dry anomaly from modest to extreme level, (De Petrillo et al., 2023) computed through the self-calibrated Palmer Drought Severity Index (sc-PDSI) (van der Schrier et al., 2013)).

Figure 3 highlights the soy sourcing municipalities of ADM and Bunge in 2018. If compared to Figure 2c, it shows an overlap between high uWF values and drought probability in Northern-Eastern municipalities. This overlap extends also with areas of high deforestation risk,

primarily in the Amazon and Cerrado biomes (Pendrill et al., 2022), where deforestation disrupts the hydrological cycle, threatening soil moisture availability for agriculture, and with substantial irrigation demand in the southern region, Brazil's most intensively-irrigated area (ANA Brazil, 2017).
The sub-national heterogeneity of TNCs' unit WF distribution provides evidence of different climatic threats and water-use issues TNCs have to face and manage.

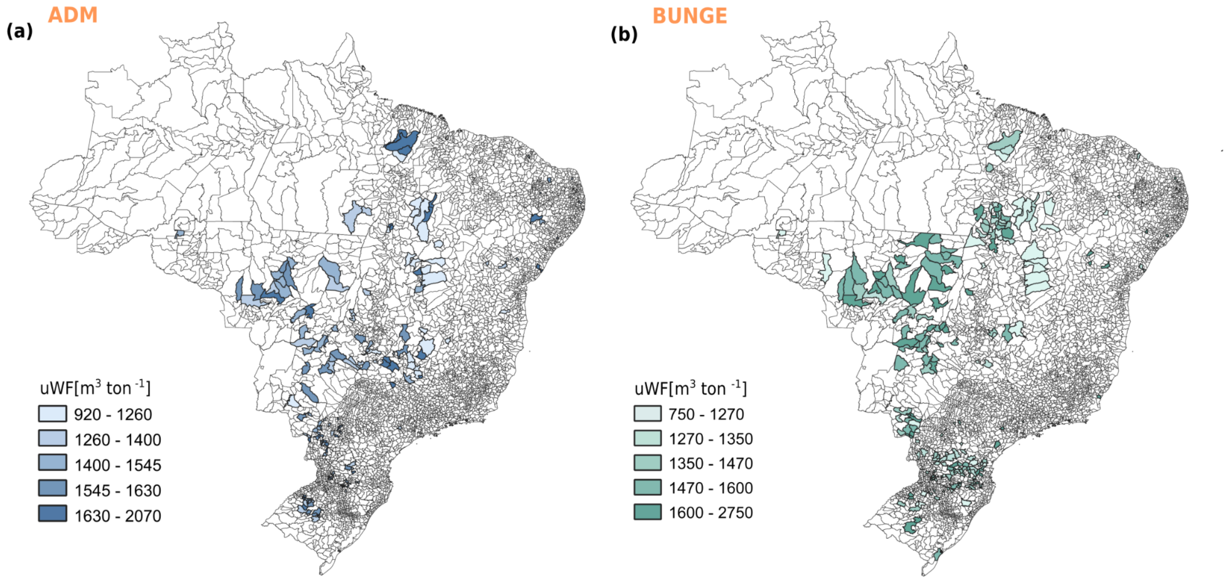

Figure 3. Soybean unitary water footprint (uWF, in m3.ton-1) associated with the export of **(a)** ADM and **(b)** BUNGE from Brazil in 2018. Figure adapted from De Petrillo et al., 2023

TNCs can take the lead in improving the water sustainability of food supply chains given their dominance with respect to countries, with only China importing larger volumes than the top corporations (Figure 1). In 2018, Bunge (15 Gm3) displaced almost four times the VW volume imported by Thailand (4 Gm3), and Louis Dreyfus (11 Gm3) displaced more than twice the VW of the Netherlands (5 Gm3), the first European importer.

While WF provides a measure of water consumption (Vanham et al., 2019), it does not account for water overuse or local water stress, which are critical aspects of water risk assessment. To construct a comprehensive framework for corporate water sustainability and risk assessments, additional dimensions such as the renewable water supply must be considered in parallel. Table 1 outlines specific indicators across various water sustainability dimensions and preferred methods, eventually connectable with virtual water trade methods and indicators.

Table 1 - Indicators related to water sustainability of food supply chains at different scales

	Indicator	**Water sustainability dimension**	**Preferred method**	**Proxy method**	**Example proxy source**
Production (farm)	Crop unit WFs / water productivity (m3/t)	Economic	Farmer measurement	Crop modelling; derive from census/ statistics existing databases	
	Crop unit blue WFs/ blue wp (m3/t)	Economic	Farmer measurement	Data on water concessions	Local or national water authorities databases
	Crop unit grey WF / grey wp (m3/t)	Economic	Farmer measurement		
	Total WF /water consumption (m3)	Environmental	Farmer measurement		
	Total blue WF (m3)	Environmental	Farmer measurement		
	Total green WF (m3)	Environmental	Farmer measurement		
	Total grey WF (m3)	Environmental	Farmer measurement		
	Area Equipped for Irrigation	Economic / resilience	Farmer measurement		Global dataset e.g, MAPSPAM, national census statistics
	Irrigation type/practice	Economic/ resilience	Farmer reporting		National census statistics
	Legal permit /water right in place	Social	Farmer / authority reporting		
	WASH available for workers	Social	Farmer / auditor reporting		
	Directionality*				
	…				

Enabling context	Aridity index	Environmental/ Resilience	Local gauging stations, RS, existing databases, …		UNEP sc-PDSI
	Blue Water Scarcity	Environmental	Catchment modelling	Global databases	SBTN, WFAT, AQUEDUCT
	Regional soil moisture depletion	Environmental			
	Water Pollution Levels	Environmental			
	GW depletion	Environmental			GRACE, PCR-GLOBWB
	Nearness to WF benchmark (%)	Economic	Nearness to WF with BAT	Global /crop databases	Mekonnen et al 2014
	Land grab risk/ occurrence	Social	In situ observations; data on contracts and actors involved	National or global databases	Land Matrix initiative (https://landmatrix.org/)
	Local regulatory landscape	Social	Farmer reporting	Local/ national / regional authorities	EU CSDDD, EU CSRD
	Water markets	Economic			
	Directionality*				

	Indicator	**Water sustainability dimension**	**Preferred method**	**Proxy method**	**Example proxy source**
Supply chain (agri-food corporations)	Volume of VW managed (m3)	Economic	AFC reported	VW trade network analysis, input-output modelling	TRASE initiative (https://trase.earth/)
	Volume of VW managed from low-productive sites (% / m3)	Economic	AFC reported	Existing databases	

	Volume of VW managed from catchments with BWS>1	Environmental	AFC reported	Existing databases	SBTN for Water
	Volume of VW managed other characteristics				
	Number of sites / farms / countries buying from	Economic / resilience			
	Number of sites / corporations / countries selling to	Economic / resilience			
	Disclosure of corporate water policy	Social	AFC reported	External validation, reporting initiatives	CDP Questionnaire
	Quality of corporate water policy	Social			
	Corporate water / WF reduction targets	All	Farmer measurement		
	Board-level oversight on water		Farmer measurement		
	Organisational capacity on water		Farmer measurement		
	Directionality*				
	…				
Enabling context	Regulatory landscape	Social	AFC reporting	Local/ national / regional authorities	EU CSDDD, EU CSRD
	Reputation	All			
	Shareholder voting profile	Environmental	AFC reporting	External validation	SEC (?)
	Supply chain coverage / big or small player	Resilience			
	Directionality*				

For example, the Groundwater Depletion (GWD) indicator (Dalin et al., 2017) quantifies globally the amount of non-renewable groundwater abstraction to sustain irrigation practice, separately for 26 crops. The GWD provides the volume of groundwater that is abstracted for irrigation use in excess of the natural recharge rate and irrigation return flow, accounting for environmental flow requirements, and thus corresponds to a measure of an unsustainable use of groundwater for crop production. Connecting the GWD with supply chains mapping data allows one to identify actors and crops contributing to global GWD, highlight key players in the production, trade and consumption of crops irrigated from overexploited aquifers, and point out associated risks for local and global food and water security. While the GWD expresses a volumetric measure of unsustainable groundwater use, another indicator, the Water Debt (WD) (Tuninetti et al., 2019) offers an evaluation of the sustainability of water withdrawals, measured as the time required for natural systems to replenish the annual water consumption for agricultural crops. By unfolding the responsibilities behind unsustainable freshwater use, WD complements WF and GWD analysis and provides insights for assessing water-saving strategies and developing future scenarios.

Additionally, indicators such as area equipped for irrigation and irrigation practices can address resilience, offering insights into adaptive capacities against water scarcity, while social indicators such as the presence of legal permits and water rights and the assessment of their just allocation may underscore equitable access. Other essential social factors, including water access, sanitation, and hygiene (WASH) availability for workers, ensure that human needs are considered in sustainability assessments.

Beyond farm-level production indicators, the enabling context of water resources must also be incorporated. Environmental resilience indicators, including the aridity index and blue water scarcity, can be sourced through local gaging stations, remote sensing, and existing global databases like the one from the United Nation Environmental Program (UNEP), AQUEDUCT (WRI). Soil moisture depletion and groundwater depletion indicators, such as those derived from GRACE data (NASA) or hydrological modelling (e.g., PCR-GLOBWB model) are increasingly critical as they highlight the pressures on regional water resources. These indicators enhance the understanding of water dependencies and sustainability under varying climatic and anthropogenic pressures.

Furthermore, an equitable sustainability framework must address water access, particularly in regions facing economic water scarcity (Rosa et al., 2020; Vallino et al., 2020). Large-scale agricultural practices can strain local water access, limiting resources for smallholder farmers and intensifying issues like water grabbing (Rulli et al., 2013; Dell'Angelo et al. 2018; D'Odorico et al., 2024a) and social water injustice (D'Odorico et al., 2024b). Broader indicators built on *land grab* and large scale land acquisition data (e.g from the LAND MATRIX database) provide additional context for understanding social risks associated with water use (Chiarelli et al., 2022).

Environmental pollution levels, including *water pollution levels* and proximity to best available technologies (BAT) for water conservation, also factor into sustainability assessments.

The presence of *water markets* and *water scarcity pricing* mechanisms reflect local economic conditions, while *benchmark proximity*—how near a crop's water usage is to efficiency benchmarks—serves as a proxy for assessing adherence to best water management practices (e.g. Karandish et al 2018).

These indicators are available at a spatial scale which depends on data availability but could be potentially available at any scale, enforcing the point that resolution of the assessment depends on data transfer and data transparency. Other indicators are more significant if referred to basin or biome in a perspective of water and biosphere stewardship.

This multi-dimensional approach synthesizes indicators into a Virtual Water Trade (VWT) framework that maps water impacts and risks across the supply chain. This framework enables TNCs to pursue sustainable sourcing by targeting regions with lower water stress and risks. The collaboration between science and corporate actors allows for high-resolution assessments, enhances transparency, and supports more effective, tailored policy-making for sustainable water use. By aligning environmental, economic, and social sustainability goals, the VWT model fosters corporate responsibility in water management, benefiting both the private sector and broader societal sustainability. The VWT framework also supports transparency initiatives, helping to map water impacts from production to consumption. TNCs can drive sustainable change by focusing on regions with minimal water pressure and sharing detailed data to improve supply chain mapping and assessment (CDP, 2024; Sustainable Food Trust).

However, to comply with accurate indicators, TNCs must provide *detailed and open data* which is needed to reconstruct sustainability and risk of the supply chain. Meanwhile, TNCs can use a tool such as VWT to better assess their supply and enrich this assessment with more comprehensive indicators by integrating local pressure indicators covering all aspects of water sustainability (including but not limited to: blue WF, WD, economic/social water scarcity, water stress). Besides, countries can take advantage of a more detailed water footprint and risk assessment to enhance the sustainability and resilience of their supply chains. In this way, countries could design more effective and targeted water policies for both their food imports and domestic production. This mutual collaboration additionally provides detailed information for consumers (e.g. water footprint labels) that turn into more sustainable patterns of consumption and active societal awareness. This mutual cooperation allows TNCs to enhance their assessments, science to gain detailed data, policymakers to frame targeted water policies while enabling science and the private sector to co-produce data and tools that better inform water sustainability practices, benefiting both corporate and societal sustainability.

3. Current evaluation of *wat*er sustainability and water-related risk by agri-food corporations

Agri-food TNCs have started to recognize their exposure to water-related risk, though the metrics they use do not necessarily provide an comprehensive understanding of the extent to which their production systems are vulnerable to failure due to water shortage, nor how their business operations negatively impact water systems. At the same time, most major agri-food TNCs carry out environmental impact and sustainability evaluations without connecting the dots between their water usage statistics and water risk exposure.

Specifically, water risk is often expressed by looking at the effects of climate change, growing competition, weak regulations, failing infrastructure, and water pollution (CERES, 2021). At the same time, business risk has been related to market factors (e.g., inconsistent or reduced water supply), reputational risk (e.g., impacts of advocacy campaigns against brands that are found to use water unsustainably), regulatory and litigation risk (e.g., mandates to reduce water consumption, water rationing, reallocation of water rights, or denial of water license renewals), transitional risks (e.g. associated with investments needed to transition to more sustainable practices) and operational risk (e.g., production reduction). Collectively, these business-related risk factors translate into decreased revenue and increased costs (CERES, 2021).

According to recent assessments by the non-profit advisor CERES, about 70% of corporations account for water risk in planning activities and investment decisions. However, corporate considerations of water risk and water sustainability remain fragmented and incomplete. In many cases, there is a clear absence of an accounting for context - particularly with regard to the status of water demand and water availability in the locations where TNCs' upstream supply chain needs are met. This indicates a pressing need for tools that assist TNCs in mapping out the multiple points at which issues of water sustainability enter into specific indicators of water risk. To further evaluate how agri-food TNCs understand, measure, assess, and provide data on water sustainability and water-related risk, we analyzed public-facing corporate documents disclosed by some of the world's largest agri-food TNCs. Since the global agri-food sector comprises companies deploying a highly diverse set of business activities (from primary food production, processing, trade, and shipping, to the provision of fertilizers, pesticides, livestock pharmaceuticals, machinery, and equipment), identifying the largest corporations is no straightforward task. However, **ADM, Bunge, Cargill, LDC, COFCO,** and **Amaggi**, are among the sector's giants. With global operations and a collective revenue of USD 441 billion in 2023 , it is clear that the views on water sustainability and risk espoused by these key TNCs provide a relevant perspective.

For each of these six TNCs, we retrieved public-facing corporate documents that may contain water-related information, such as Sustainability Reports, environmental, social, and governance (ESG) Reports, and—if applicable—CDP Water Reports. We retrieved the most recently published documents from 2022 and 2023. Next, we formulated sixteen questions, the answers to which we obtained from these documents. See Table S.1 for profiles of the TNCs evaluated and SI (**Supplementary file**) for an overview of the questions and our detailed scoring of each.

Evidenced by the low scores all TNC's received on our questions (see SI X), we find that these TNCs' reporting on water-related matters is incomprehensive and falling short of addressing many of the risk and sustainability dimensions outlined in previous sections. , Moreover, their disclosures do not provide the desired water-related data on value chains that only these TNCs can provide. If water is reported on at all, the reason for and focus of the reporting is, without exception, on how water — or a lack thereof — may present risks to the company's operations and therefore to their bottom line. Consequently, the reporting is designed to address the question of how the company is seeking to mitigate these water risks. That said, the reporting depth and diligence on the topic of water differs greatly between the six TNCs, with Cargill showcasing the most comprehensive reporting on water by a wide margin compared to the rest.

None of the TNCs present water explicitly in terms of sustainability, i.e., how their direct operations or the value chains over which the company has an influence may negatively affect water systems. In other words, the TNCs assume a narrow, inward focused perspective on water, rather than an outward one that considers how their activities impact society and the environment (i.e., double materiality perspective, cf Hogeboom et al (2018)). Cargill is the only company for whom it could be argued included water sustainability concerns as well, albeit without direct referral to the concept. As part of their CDP reporting, Cargill is asked about their water impacts, to which they respond in terms of their water pollution management, their (positive) impact through regenerative agriculture programs, and by assessing suppliers' impact on water security (Cargill, 2023a)). Moreover, Cargill introduces a different water concept, namely water positivity, which they describe as "effectively improving watershed health by addressing the shared water challenges of availability, quality, and access to safe drinking water, sanitation, and hygiene (WASH), using an approach that is informed by our footprint and the severity of local water challenges" (Cargill, 2023b).

TNCs report on various indicators that reflect their dependencies on water resources. Indicators used include water withdrawn, water intensity, water discharged, water consumed, and water used. All physical quantity indicators refer to blue water, that is, water from surface water or groundwater sources. Even though precipitation held within the soil, i.e. green water, constitutes the majority of total crop water consumption in many regions, this water source is not considered by any of the TNCs evaluated. It implies that TNCs seem to think that only blue water shortages can induce water risks. Bunge, for example, understates their water consumption and dependency by excluding green water, noting that "The majority of the crops that Bunge sources are rainfed, meaning they do not typically require irrigation. That makes the freshwater intake of our commodities relatively low." (Bunge, 2023). However, rainfed crops are all the more susceptible to drought-induced water stress than are irrigated crops—even though the latter clearly have downsides of their own, such as depleting blue water resources.

If water targets are set, they are expressed in related terms of reduction of water intensity, withdrawal, and consumption. Although each of these concepts carry a different meaning, terms are typically ill-defined and occasionally used interchangeably. For example, ADM formulated a target on water withdrawal—typically understood as a gross use term—but seems to equate withdrawal with consumption, a net use term: "We have decided to refocus our water goal as an absolute reduction of water withdrawal. By 2035, we will reduce our absolute water consumption 10% over a 2019 baseline." (ADM,2022).

Importantly, water accounts and targets typically only refer to direct operations of the company. They thereby overlook the often much more water intensive supply chain. Cargill, and to a lesser extent also ADM, are the only ones for whom the supply chain is within their reporting scope. For example, Cargill reports on agricultural products from regions with high water stress and low water availability in the supply chain. Cargill also put forward a water stewardship target, which includes watershed restoration activities and improving access to water, sanitation, and hygiene (WASH) facilities (Cargill, 2023b).

Four out of the six TNCs disclose some information on the tools, methods, or data used for their water reporting, ranging from references to generic 'environmental monitoring programs' to more specific tools such as water footprint assessment or the Aqueduct Tool (World Resources Institute, n.d.). The most comprehensive disclosures are once more from Cargill, particularly in the context of their CDP reporting. They report, among others, that they collect and use local data from various facilities they operate, such as water metering or water bills, but they also use global or simulated water data. Moreover, Cargill claims to have "mapped our agricultural supply chain data and calculated the impact of these agricultural commodities." (Cargill, 2023a). However, neither Cargill or any of the other TNCs share or provide access to such data.

In sum, the corporate perspective on water espoused by some of the largest TNCs in the sector reflects a restricted understanding of water-related themes. If reported on at all, the focus is on how water may harm the company rather than how the company may harm water systems. Indicators, methods, and targets related to water are oftentimes ambiguous and only superficially reported upon. Water-related data, particularly on value chains which only these private players can provide, is not shared or made accessible.

Table 2. Summary of findings from assessing corporate disclosures on water. For a detailed scoring of the TNC's assessed, please see the SI spreadsheet.

Reporting aspect [1]	**Synthesized answers from corporate disclosures**
Motivation to report on water	Water is material to the company, i.e., it may affect their income
Concepts used	o Water risk o Water impacts o Water positivity o Water stewardship
Accounting for water use/pollution	o Water withdrawn o Water intensity (in m^3 per monetary unit of revenue) o Water discharged o Water consumed o Water used o Agricultural products from high water stress regions o Water availability in the supply chain

Goals or targets set	o Reduction of water intensity o Reduction of water withdrawal o Reduction of water consumption o Water stewardship o Watershed restoration o Improve access to WASH facilities
Tools, methods, data	o Environmental monitoring program o Fauna and flora surveillance o Soil and water quality analysis, o Proactive inspection of disturbed land o World Resource Institute's Aqueduct o Water footprint assessment o Water stress exposure assessment o Continuous online monitoring of priority facilities o Continuous water metering o Water bills o Water tracking system o SBTN GCA 2020 o OECD (2017) o Water Risk Hotspots for Agriculture

[1]If provided. See SI spreadsheet for a breakdown by agri-food company on each of the reporting aspects.

4. Discussion

a. Opportunities for agri-food corporations to improve water resilience and sustainability

Advancements in technology and science are enabling new opportunities for TNCs to simultaneously reduce their water risk and enhance their sustainability. A broad - and growing - array of tools are available to inform corporate policies on water risks and sustainability that are scientifically-grounded, with measurable, testable, and verifiable indicators. These approaches can enable the evaluation and benchmarking of current status, gauging progress over time, and informing decision-making based on timely, accurate, and relevant data. These tools can provide the necessary data foundation necessary to enable transparency and science-based decision-making throughout the supply chain.

Ideally, water risk and sustainability assessments would be underpinned by data directly metered and measured at the farm or facility scale, with verification along trade routes and each processing stage. Additionally, emerging technologies such as blockchain show promise in enhancing transparency and traceability. However, several challenges impede this ideal scenario, including cost constraints, farmer and supplier buy-in, technical challenges, issues of scale, and supply chain tracking uncertainties. When ideal data is unavailable, TNCs often rely on aggregated data from government censuses, surveys, models, or remote sensing. Although these may yield relevant proxies, particularly TNCs could arguably leverage their influence more by encouraging their farmer-suppliers to measure and provide said data. Simultaneously, investments in technology and scientific advancements are needed to improve data quality, harmonize collection efforts, and increase coverage. Governance and institutional arrangements could further facilitate data collection and sharing, and cross-scale and cross-actor analyses should be improved.

Specific data requirements at the farm level include irrigation census per specific crop (with potential cross-verification using satellite data), crop maps detailing crop types, fertilization, and management characteristics, and mapping of water systems resilience and robustness. For the supply chain, detailed data linking producer municipalities to trading TNCs, and importing countries and corporations is crucial. An initiative similar to Trase (trase.earth) for deforestation risk could be beneficial for water risk assessment in the agri-food sector. By also tracing the trade path and mode of transport of goods vertically through their supply chain, corporations can quickly assess bottlenecks in their supply chains related to the failure of critical infrastructure, drought, or floods that may inhibit the movement of barges or cargo vessels.

There is a need to strike a balance between highly contextualized insights and generalizable, comparable findings. This requires analyzing where uncertainty in estimates is acceptable and where more accurate data or better models are critically needed. Contextualizing current indicators is essential to avoid misleading conclusions. Determining what type of information should be gathered and shared to achieve this balance is a key consideration for researchers and policymakers alike. To address these gaps, new scientific approaches are needed to help TNCs identify and quantify diverse water-related risks and sustainability challenges accurately. In the interim, proxy indicators such as progress on Sustainable Development Goals (SDGs) or Water, Sanitation, and Hygiene (WASH) metrics may provide valuable insights until more specific metrics are developed.

b. How to facilitate adoption by companies of opportunities improve water resilience and sustainability

It is clear that a growing set of tools are available for TNCs to assess and track the sustainability of their supply chain decisions and to better ensure that objectives of water sustainability and risk management are aligned (and do not compromise other dimensions of sustainability (Davis et al., 2022)). However, more is needed than the advancement of technology with which TNCs can monitor and evaluate the sustainability of water use in their supply chains for them to conserve water, which makes sense as making a profit is the main goal of a company. Yet, TNCs have a unique ability to influence the use of water resources, since they are vertically integrated and relatively few in number for the supply chains of certain commodities, (Davis et al., 2021). This means that TNCs will likely not adopt water-savings technologies (or incentivize adoption by their suppliers) unless it leads to cost-savings. Resolving this discord between the core motivations of TNCs (i.e., to be profitable) and the capacity for sustainable change that they possess is where policy levers may play a key role.

Importantly, addressing water risks is not just about mitigating negative impacts; it also presents significant opportunities for TNCs in the agri-food sector, such as building resilience and improving sustainability of operations. However, a 2022 CDP survey (CDP 2023) revealed that 44% of food, beverage, and agriculture respondents did not disclose a single water-related opportunity, despite the critical role water plays to the sector. This finding underscores the need for these corporations to prioritize the identification of such opportunities strategically. Corporations that integrate water into their long-term business strategy are better positioned to capitalize on these opportunities. National governments play a key role in accelerating opportunity identification by strengthening the regulatory environment for corporations to act on water.

Indeed, a range of soft and hard regulatory nudges and market signals can play an important role in encouraging corporate adoption of improved water resilience and sustainability practices. For instance, scientific communities can develop strategies to make literature more accessible and applicable to industry needs. Creating platforms for collaboration between academic researchers and corporate stakeholders can facilitate knowledge transfer and the development of practical solutions. Encouraging the development of user-friendly tools that translate complex scientific findings into actionable insights for corporations can bridge the gap between academic research and industry practice. More firmly, government regulations can play a crucial role in requiring certain levels of adoption. This could involve actions such as mandating data sharing and reporting in order to address issues in which corporations do not have comprehensive knowledge of their input sources or production methods. A suite of coordinated and properly structured incentives and regulations can help bring corporate water use within sustainable levels, lower barriers to the integration of water sustainability accounting, and ensure a more accurate valuation of water throughout a company's supply chain (Barrett et al., 2020). For instance, governments can subsidize Research and Development (R&D) costs for corporations to innovate their supply chain tracking as well as their assessment of water risk; doing so can reduce the financial burden on the private sector, make TNCs more willing to share innovations with other corporations, and more effectively facilitate the identification of industry best practices (Herrero et al., 2020). Accompanying the encouragement of improved supply chain tracking - and in particular, detailed geospatial information - will be a need for improved data governance that ensures privacy and benefits-sharing while also promoting increased transparency, quality control, and reliability of data from corporation self-reporting (World Bank, 2021). Governments can also employ market forces - such as water markets (Debaere et al., 2014) for both surface and groundwater or block rate charges - which are meant to better reflect the true value of water in the decision-making process for corporations and other water users. Because much of the supply chain water footprint - particularly for agricultural commodities - originates at the production step, interventions and incentives to promote less water-intensive crop choices (e.g., guaranteed prices for farmers (e.g., Davis et al., 2019)) and to encourage adoption of more water-efficient on-farm practices (e.g., Marston et al., 2020) can contribute substantially to improving the water sustainability of corporate supply chains. One way this can be achieved is by developing economic systems that provide a time-varying price signal of water – where price increases when water is more scarce – can help corporations properly account for the scarcity value of water. For example, irrigation water supplies are an often underpriced input in agricultural production, so producers likely focus on minimizing other, more expensive, inputs, rather than reduce their water use. In all of these potential interventions, it will be essential to couple the technological innovations needed for comprehensive supply chain tracking with enabling economic conditions and policy environments in order to meaningfully enhance the likelihood that corporations will adopt water sustainability measures (Herrero et al., 2020).

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5. Conclusion

This review of current data and practices around water-related risks and sustainability of water use in food supply chains shows that there is the potential to significantly improve the metrics currently used by food supply chain corporations. When considered, their significance, robustness, as well as their temporal and spatial coverage and detail does not allow accurate or transparent assessments. Besides, a lack of standards as well as a lack of transparency are detrimental to regulators and consumers.

Addressing water risks and sustainability in the agri-food sector requires a multifaceted approach that combines improved data collection and transparency, scientifically-grounded corporate policies, and collaborative efforts between academia, government, and industry. By implementing these strategies, stakeholders can work towards more sustainable water use in food production and sourcing, as well as enhanced resilience to water-related risks. Future research should focus on developing more comprehensive risk assessment models for critical TNCs in the “missing middle” that incorporate the full spectrum of water-related risks, improving data collection and sharing mechanisms, and creating tools that facilitate the integration of scientific knowledge into corporate decision-making processes, as well as government regulations that guide these decisions.

Ultimately, a water-secure world requires actors in agri-food systems, including important middle-men and TNCs, to consider water risks in their business practices. Fully integrating water into corporate strategies and ensuring accountability for water targets is essential to achieve a more sustainable and resilient agri-food sector in the face of increasing water scarcity and climate change challenges. The journey towards water security in the agri-food sector will enable companies to balance risk mitigation, with existing efforts to promote innovation, growth, and sustainable development.

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Supplementary Information

Table S1. Profiles of agri-business corporations evaluated in this study.

Company name	***Revenue*** *(2023 Billion USD)*	***Headquarter***	***Description*** *(adapted from Bloomberg company profiles)*
Cargill	*177*[a]	*USA*	*Cargill produces grains and oilseeds and provides farmer services and risk management solutions. It also offers animal nutrition, biofuels, meat and poultry, food, and industrial products.*
ADM	*94*[b]	*USA*	*Archer-Daniels-Midland Company (ADM) procures, transports, stores, and merchandises agricultural commodities and products. ADM processes oilseeds, corn, milo, oats, barley, peanuts, and wheat. ADM also processes products which have primarily two end uses including food or feed ingredients.*
Bunge	*60*[c]	*USA*	*Bunge Limited operates as a global agribusiness and food company. Bunge buys, sells, stores, transports, and processes oilseeds and grains to make protein meal for animal feed and edible oil products for commercial customers. Bunge also produces sugar and ethanol from sugarcane, mills wheat, and corn, as well as sells fertilizers.*
LDC	*51*[d]	*Netherlands*	*Louis Dreyfus Company B.V. (LDC) operates as a merchant and processor of agricultural goods. LDC provides animal feeds, fertilizers, agricultural chemicals, and other farm supplies.*
COFCO	*50*[e]	*China*	*COFCO Corporation operates as an agricultural products supplier. COFCO supplies edible oils, corn, wheat, rice, vegetables, sugar, and other products. COFCO also operates real estate development, finance, and other businesses.*

Amaggi	*9*[f]	*Brasil*	*Amaggi Exportacao e Importacao Ltda produces and distributes agricultural products. Amaggi processes grains and fertilizers.*

[a]*https://www.cargill.com/about/doc/1432242761261/2023-cargill-annual-report.pdf*

[b]*https://www.annualreports.com/HostedData/AnnualReports/PDF/NYSE_ADM_2023.pdf*

[c]*https://investors.bunge.com/~/media/Files/B/Bunge-IR/documents/shareholder-meeting-materials/bunge-2023-annual-report.pdf*

[d]*https://www.annualreports.com/HostedData/AnnualReports/PDF/louis-dreyfus-company_2023.pdf*

[e]*https://www1.hkexnews.hk/listedco/listconews/sehk/2024/0430/2024043002848.pdf*

[f]*https://www.amaggi.com.br/wp-content/uploads/2024/06/AMAGGI-2023-ESG-Report.pdf*