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Agricultural trade: Impacts on food security, groundwater and energy use

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Introduction

Trade in food and agricultural products has more than doubled in real terms since 1995. Emerging and developing economies have joined countries in the Global North as dynamic participants in global markets, and now account for about a third of global trade [1]. In general, countries in Latin America, East Africa, and South Asia are net food exporters while most of the rest in Asia and Africa have remained food importers (Figure 1).

Global production of primary crops increased by 53% between 2000 and 2019, to a record high of 9.4 billion tonnes in 2019. This increase in production has been mostly due to intensified use of irrigation, pesticides, and fertilisers, and to a lesser extent to larger cultivated areas, better farming practices, and high-yield crops [2].

Increasing food exports have strengthened local and global food security. On the negative side, they have severely harmed freshwater ecosystems. Surface and groundwater exploitation have resulted in saline intrusion, declining groundwater tables that affect other users, land subsidence, reduction of flow in streams, lakes and wetlands, loss of biodiversity, and heightened greenhouse gas emissions. Intensive use of pesticides and fertilisers, as well as chemicals, pharmaceuticals and pathogens introduced due to untreated sewage, have also caused serious pollution [1,4].

Globally, most of the water that is used (60%—70%) is groundwater. Its use in irrigation has increased both as a percentage and in absolute terms. It was calculated at 820 km^3/year in 2018 based on aggregated country-level reports the same year [5]. It is estimated that of all the area equipped for irrigation, over 30% depends on groundwater [6].

Studies reveal large impacts of global food demands on local freshwater resources. As agriculture becomes more water-intensive, more water is embedded in its produce, with growing international imports and exports representing a growing 'trade' in this 'virtual water' [7—11]. While this contributes indirectly towards food security, it directly affects quantity and quality of water in food-producing arid and semi-arid regions [12,13]. For these regions, it would be more sustainable, and profitable, to import agricultural products and the associated virtual water, from regions that are not water scarce. This would reduce, and even avoid, groundwater depletion and pollution in countries of destination but not in those of origin.

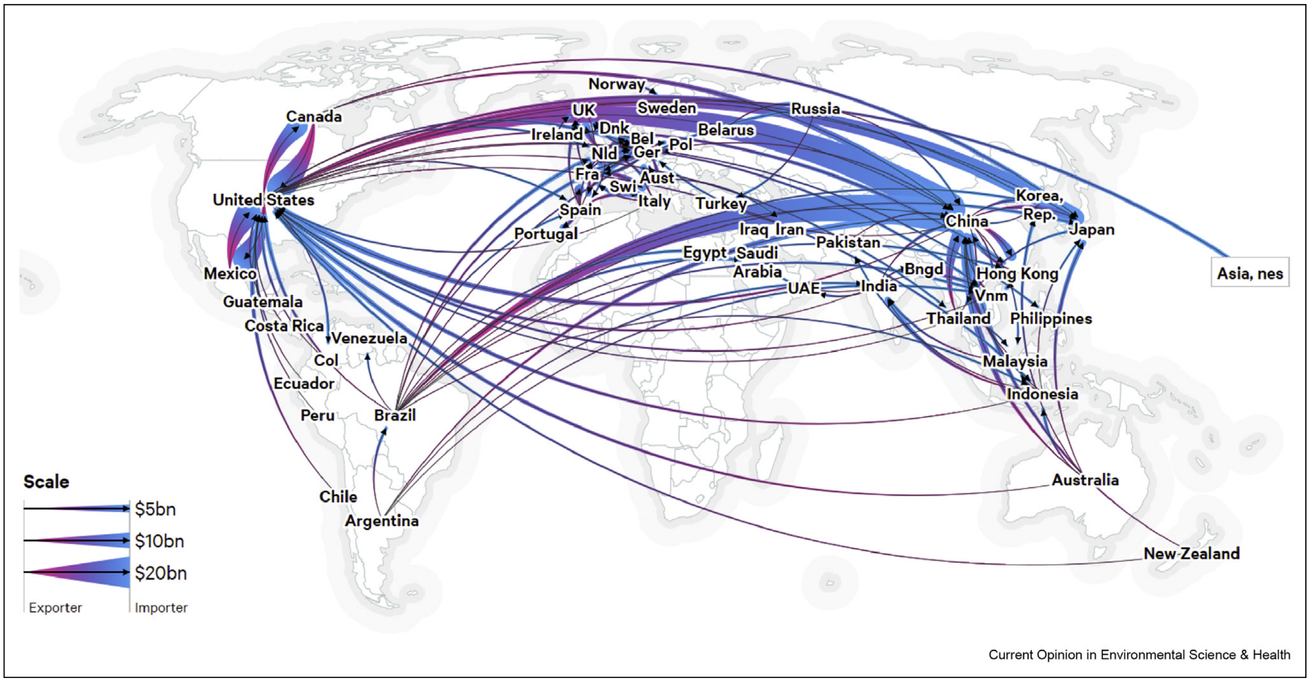
Groundwater's invisibility has led decision-makers to neglect its management. This includes conjunctive use of surface and groundwater for more efficient management, and coordination of policies among different sectors, such as water, irrigation, and energy. It also causes the various sectors to make decisions that disadvantage other sectors, often for political reasons.

In this analysis, we consider the impacts of agricultural trade on food security, groundwater, and energy use. We report on the current state of groundwater depletion in specific countries followed by an analysis on energy use, and broader policies that have the objective to protect groundwater in more countries around the world.

Groundwater-based irrigated agriculture for export

There is a clear global trend towards expansion of irrigated areas for export agriculture, which increases productivity but also results in groundwater depletion. Poor management of groundwater in countries in both the

Figure 1



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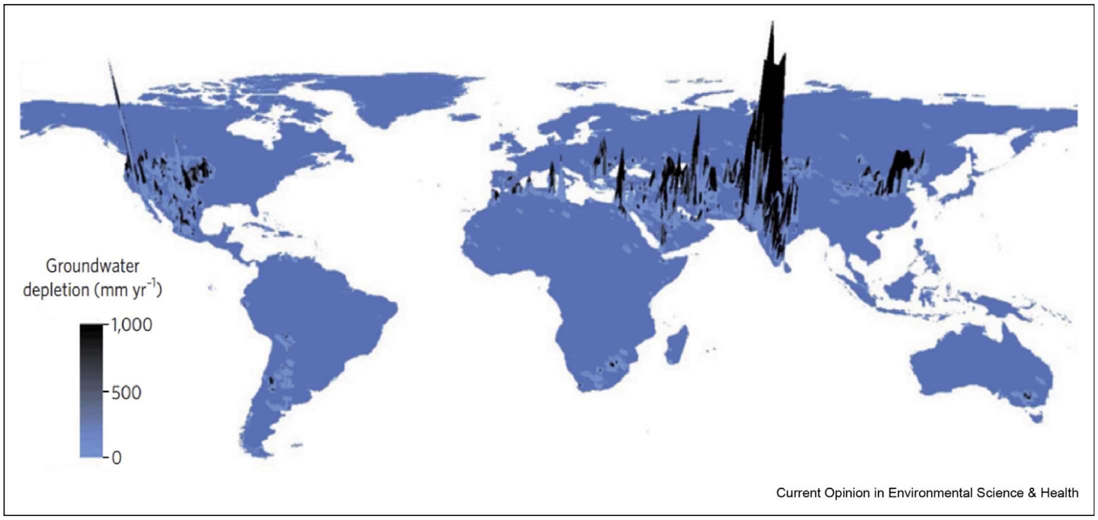
Export of agricultural products in 2015 by value (USD), map by Applied Works [3].

Global South and North has resulted in localised depletion of aquifers (Figure 2), seasonal exhaustion, and pollution.

A country where agricultural production depends greatly on aquifers that are already depleted and polluted is India [16]. It is the largest user of groundwater for irrigation and a main contributor to the global food basket. Approximately 90% of the groundwater that is extracted is used to irrigate 60% of land area through more than 21 million privately owned wells [17], supporting more than 90 million rural households [18]. India produces approximately 10% of all global agricultural outputs and is the second-largest producer of wheat and rice. From April 2020 to February 2021, the country exported pulses and dairy products worth US

Figure 2



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Recent estimate of the global distribution of groundwater depletion. The three-dimensional topography [14] shows ‘mountains of groundwater depletion’ especially in the United States, Mexico, Saudi Arabia, Pakistan, India, and China [15].

$261 million and US $183 million, respectively. The total value of its agricultural exports is on track to grow to US $60 billion by 2022. Nevertheless, most of these exports are grown in the arid or semi-arid parts of the country [19] and rely on groundwater that is over-exploited and polluted. It is estimated that, in 2010, India exported approximately 25 km^3 of virtual water in its agricultural exports. This is equivalent to annual water demand of approximately 13 million people [20], threatening water and food security and local livelihoods [21].

In the United States, also one of the most important countries in global food trade, despite recent gains in water use efficiency, groundwater withdrawal for irrigation has almost tripled since records began in 1950. Consequently, depleting groundwater in many more areas across the country [22]. The High Plains, known as the 'grain basket', and the Central Valley, known as the 'fruit and vegetable basket', are ranked first and second, respectively, among aquifers in the United States for total groundwater withdrawals [23]. In 2019, California exported approximately 28% (by volume) of its agricultural production, earning $21.71 billion in sales [24]. Its dependence on groundwater for irrigation continues to increase, threatening further aquifer sustainability, and therefore future crop production.

In Mexico, over the past three decades, the state of Guanajuato, in the highlands of Central Mexico, has become the leading supplier of fresh vegetables and fruits to the United States [25]. In 2016, irrigation of 250,000 ha consumed 84% of all extracted groundwater [26]. In 2017, more than 4000 Mm^3 of water was used for irrigation. Unsustainable practices have resulted in overdraft of more than 1000 Mm^3/year, with pumping depths sinking to more than 200 m below the surface, and aquifer levels dropping on average 2–3 m/year [27]. Growing arsenic and fluoride contamination threatens public health, and, as in California and India, land subsidence that affects channels and drains are common [28]. As in many other regions, agricultural production and intensive irrigation have not considered the recharge capacity of aquifers, which are now severely depleted [29]. If the same practices continue, the estimated balances for 2036 show very large deficits, putting food production at risk [30].

In Ica Province in Peru, the agro-export companies have transformed the desert into farmland. Crop production for export (especially asparagus) depends on groundwater extraction from the Ica-Villacurí aquifer. The production area increased from 7400 ha in 1997 to 22,000 in 2013. As a result, groundwater use more than tripled within this period [31], and the groundwater table has sunk by 1.5–4 m per year [32]. In 2012, surface water demand totalled 250 Mm^3 for more than 5800 users, while demand for groundwater was 300 Mm^3 for 10 users, all of them companies, threatening small farmers and domestic water users [33]. With the objective to protect the aquifer, well digging has been prohibited. However, in the absence of monitoring, construction of illegal wells has increased. It has been estimated that 76% of the cultivated area in the Ica Valley will suffer severe water shortages within 10 years.

In Spain, expansion of groundwater-based irrigation (3.8 million ha in 2020) has brought significant socioeconomic development [34] but also increased deterioration and pollution of groundwater in specific regions and basins. In 2019, the country exported 14 million tonnes of fruit and vegetables (7.7% more than in 2018), mainly to elsewhere in Europe, earning over €13 billion (5.5% more than in 2018). Irrigation systems have become more efficient, but they have not resulted in water savings. This is because irrigated area has expanded with the proportional use of groundwater for irrigation growing from 17.5% to 24%, and the volume rising from 3189 Mm^3/year to 4142 Mm^3/year [35] (30% increase in water abstraction), exacerbating overdrafts.

Water efficiency alone has not been the solution. There is a rebound effect that encourages greater use of resources: more land, more water, more fertilisers [36]. Examples include China [37,38], Spain [39], Australia [40], India [41] and so on. Without incentives to moderate water consumption, there is a strong risk of over-exploitation and even depletion of water resources. The importance of groundwater is recognised. However, policies to remediate environmental problems have been slow to be implemented nearly all over the world [42].

Groundwater extraction and energy use

Groundwater resources typically use about 30% more energy than do surface water supplies [43]. Subsidies on fuel (diesel, petrol, butane) or grid electricity for agricultural use have resulted in over-abstraction of surface and ground waters. They have driven inefficient and energy-intensive water use by hiding the true cost of the resources [44]. They have also been very expensive for governments. In Morocco, they have represented up to 6% of the national GDP [45].

India is the fourth-largest energy consumer globally, partly due irrigation pumping, encouraged by subsidies. In 2003–2004, around 12.8 million electric pumps, with a total of 52 GW (GW) of connected load, consumed 87 billion kilowatt-hours (kWh) of electricity. In 2017, irrigation consumed 17% of energy produced at the national level [46]. Energy subsidies for agricultural groundwater pumping represent up to 85% of the actual cost of electricity. Without specific objectives and time frames, subsidies threaten the sustainability of both groundwater and the power sector.

In the North China Plain, where there are severe issues with aquifer depletion, groundwater pumping consumes an average of 13.67 billion kWh/year, and 1122 kWh/Mm^3 under the winter wheat/summer maize rotation system. The region has become one of the world's largest energy consumers for groundwater irrigation [47].

In the US, in California, it is estimated that 7000 GWh of electricity were used for groundwater extraction in 2010. More specifically, the Santa Clara Valley Water District estimates that farmers in the San Francisco Bay Area used about 1000 kWh for 4546 m^3 (1000 kWh/million gallons) for groundwater pumping [48].

While groundwater has historically been an inexpensive resource for farmers, especially where groundwater use is not regulated, rising energy prices have become a substantial problem. Even though farmers can spend as much as 25% of their average annual net income from crops on more powerful pumps to pump water out of deeper wells [49], there are no indications that rising prices are slowing groundwater withdrawals [50].

As an alternative to conventional electric and diesel pumping systems, several countries are promoting subsidised solar-powered irrigation. Their wider use will allow small and marginal farmers to pump their own groundwater instead of buying expensive water from large farmers. Solar power can also reduce GHG emissions from agriculture. On the other hand, without regulation, solar pumps will contribute to the depletion of groundwater (even if irrigation efficiency is maximised), making it unsustainable. Farmers using solar power have no financial incentive to limit their water pumping [51,52]. They can reallocate water to larger areas of land, more water-intensive crops, an additional cropping season, or higher yields. Some may sell their 'extra' water to neighbours, putting more pressure on already scarce water resources.

Given the impacts of groundwater extraction on energy, energy embedded in water savings could be measured to inform policies related to water and energy efficiency [53]. Decision makers could also consider the energy implications of water policy decisions, improve coordination among resource management agencies, assign a higher priority to water conservation and work closer with the farmers [37,54].

The future of food security under unsustainable groundwater management

Groundwater management for irrigated agriculture depends on policy, legal and regulatory frameworks, and on their implementation. It also requires an enabling environment—that is, institutional capacity and collaboration in public institutions in the various sectors (water, agriculture, energy, environment) and at all levels: federal offices and state boards, basin authorities, water users' and farmers' organisations, as well as private sector groups.

Reasons for the current situation of groundwater have been discussed before. They include poor regulation, policy, management, and governance; institutions without capacity or resources (human as well as financial) to implement plans and policies; lack of realistic and informed goals that consider aquifer roles and uses as well as limited or unreliable data and information; absence of effective processes to engage users; and the fact that politicians prefer not to increase water prices or reduce subsidies because of possible repercussions in terms of their electability.

In the Global South, long-term action plans to protect groundwater resources that are implementable, are mostly lacking [42]. There are regulations that either limit or prohibit the use of specific aquifers, but the results have been limited [55,56]. China's first national plan on groundwater pollution control [57] and India's Atal Bhujal Yojana—National Groundwater Management Improvement Programme [58] are examples of recent initiatives. If implemented, they will result in more effective groundwater protection.

In the Global North, there are more efforts to protect groundwaters. In the United States, in California, the Sustainable Groundwater Management Act was passed in 2014, with full implementation scheduled for 2041 [59]. The Act aims to stop overdraft and bring groundwater basins into balanced levels of pumping and recharge. No such plans exist in Texas, one of the five states that use the most groundwater in the country, where groundwater is not regulated.

In the European Union, the Groundwater Directive considers several measures to achieve good quantitative and chemical status of groundwater by 2015 [60]. Regulations are at different levels of implementation in the member states. The EU has also approved a regulation on minimum requirements for water reuse for agricultural irrigation [61]. Reused water is proposed as an alternative resource to improve the status of the environment and alleviate pressure on groundwater by substituting abstraction as well as by relieving pressure of discharge to sensitive areas.

In Australia, groundwater is managed by state and territory governments with the help of regulatory and economic instruments [62]. However, political decisions have resulted in poor outcomes, particularly regarding investment capital [63].

Policy interventions to protect groundwater are essential. However, in many places, overexploitation has resulted in a growing gap between water extraction and recharge, loss of surface water resources as part of the same ecological system, reduction of water available for the environment, rapid decay of traditional irrigation sources such as tanks and spring channels, stagnant irrigation canals, progressive decline of groundwater tables and deterioration of water quality. Policies to reduce groundwater extraction include water accounting, pricing water considering all its uses (including environmental and opportunity costs), higher electricity prices, water use rationing (with quantitative ceilings on water and electricity use/ha), promoting recharge, limit drilling depth and proximity of wells, encouraging farmers to grow less water-intensive crops, information campaigns, use of social media, and so on. However, without laws and regulations that are implementable, and more effective groundwater management that assesses and limits exploitation, limits irrigation area, controls illegal irrigation and use of fertilisers and pesticides, and monitors water quantity and quality, pollution and rapid depletion of aquifers have become the norm in many parts of the world.

The potential of digitalisation for a more effective management of groundwater quantity and quality is enormous. However, benefits are uneven across developing countries as availability and access to data and infrastructure are limited.

Despite depletion and pollution, use of groundwater for irrigation has benefitted local and national economies. Thus, for governments in OECD and non-OECD countries it would be almost impossible to withdraw agricultural subsidies, estimated at $700 billion/year, $536 billion of them directly to producers [64]. This, even when eliminating minimum prices or subsidies in arid or semi-arid countries for crops that are water intensive would greatly contribute to a better management of water resources [42].

Overall, we see a world with a growing gap between demand for and availability of water at local levels, with intensive agricultural practices contributing to the severe degradation of the environment, and growing virtual water trade, which in turn can threaten both livelihoods and freshwater ecosystems in origin. Additionally, the increasing frequency and duration of droughts makes it essential for public and private institutions and users alike, to understand and improve management practices. Because groundwater is crucial for agriculture, over-exploitation, coupled with drought events, has increased vulnerability at the global level.

Scholars suggest that, to adapt to climate change, regions and countries should grow less water-intensive crops [65], or convert irrigated agriculture to rainfed agriculture, even for valuable crops [66]. Neither of these changes is likely to be attractive to farmers, compared to the reliability that irrigation provides. Urgently needed are groundwater governance mechanisms with joint management of resources and appropriate forms of shared decision-making by actors at the national and local levels, and goals that are broadly agreed and locally implemented—features lacking at present.

As aquifers continue to be depleted, and global climate continues to change, pumping groundwater could become economically prohibitive and environmentally more damaging, further affecting food security, freshwater ecosystems, and livelihoods. Solutions are in the hands of governments and users. Inaction will have serious consequences for agricultural sustainability, long-term food security, community livelihoods, and economic growth.

Declaration of competing interest

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

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