Virtual groundwater transfers from overexploited aquifers in the United States

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The High Plains, Mississippi Embayment, and Central Valley aquifer systems within the United States are currently being overexploited for irrigation water supplies. The unsustainable use of groundwater resources in all three aquifer systems intensified from 2000 to 2008, making it imperative that we understand the consumptive processes and forces of demand that are driving their depletion. To this end, we quantify and track agricultural virtual groundwater transfers from these overexploited aquifer systems to their final destination. Specifically, we determine which US metropolitan areas, US states, and international export destinations are currently the largest consumers of these critical aquifers. We draw upon US government data on agricultural production, irrigation, and domestic food flows, as well as modeled estimates of agricultural virtual water contents to quantify domestic transfers. Additionally, we use US port-level trade data to trace international exports from these aquifers. In 2007, virtual groundwater transfers from the High Plains, Mississippi Embayment, and Central Valley aquifer systems totaled 17.93 km^3, 9.18 km^3, and 6.81 km^3, respectively, which is comparable to the capacity of Lake Mead (35.7 km^3), the largest surface reservoir in the United States. The vast majority (91%) of virtual groundwater transfers remains within the United States. Importantly, the cereals produced by these overexploited aquifers are critical to US food security (contributing 18.5% to domestic cereal supply). Notably, Japan relies upon cereals produced by these overexploited aquifers for 9.2% of its domestic cereal supply. These results highlight the need to understand the teleconnections between distant food demands and local agricultural water use.

teleconnections | groundwater depletion | virtual water | trade | food security

Globalization has strengthened and expanded connections between socioeconomic systems and distant resources, by enabling consumer demand in one location to be fulfilled with production and resource use in another. The distant interactions between people and places are commonly referred to as "teleconnections" (1), which represent a specific case of the complex interactions that arise between coupled human and natural systems (2). These nonlocal interactions are increasingly widespread and lead to unanticipated outcomes with profound implications for resource consumption and sustainability (3). The global food trade system is a clear example of a teleconnected system that connects local resource use with distant consumer demands. Agricultural production is a particularly water-intensive sector of the economy (4–6), such that trade of agricultural products connects local water use for irrigation to the end consumer of the commodity, in a "virtual water trade" (7, 8). In this paper, we seek to understand how distant food demands are linked with nonsustainable local agricultural water use.

Groundwater plays a critical and ubiquitous role in human society (9), providing an estimated 36, 42, and 27% of global domestic, agricultural, and industrial water uses, respectively (10). Population growth, socioeconomic development (4, 9), and, to a lesser extent, climate change (4, 11), are expected to increase future demand for groundwater resources. Unsustainable groundwater withdrawals will limit future groundwater availability (12–15), with implications for food security (16), because ∼40% of global irrigated agriculture relies upon groundwater. Importantly, ∼42% of irrigated agriculture in the United States, one of the largest food producers and the largest exporter globally, depends on groundwater (17). Furthermore, groundwater depletion will affect the ability of urban areas, over half of which are located in water scarce basins (18), to meet normal water demands and cope with climate variability, against which groundwater acts as a buffer (9).

The Central Valley (CV), High Plains (HP), and Mississippi Embayment (ME) aquifer systems (mapped in Fig. 1) enable agricultural production that is critical to local economies and contributes to US and global food security. In 2007, roughly one-fifth of the $300 billion agricultural industry in the United States came from these aquifer regions (19, 20). The lands overlying the CV (52,000 km^2), HP (450,000 km^2), and ME (202,000 km^2) make up 8% of US land area yet comprise 16% of US cropland. More than 17 million people live within the boundaries of these three aquifers. In addition, 25.7% of all US irrigation and livestock withdrawals and 61.1% of all groundwater irrigation and livestock withdrawals come from these three aquifers (17). Despite their importance, these aquifers are being managed unsustainably; 67% of US groundwater depletion from 1900 to 2008 and 93% of groundwater depletion from 2000 to 2008 is attributed to these three aquifers (21).

Much is understood about local food production and groundwater use in the HP, CV, and ME aquifer systems. It is now imperative to begin to evaluate the consumption side of the story and determine where these resources are being demanded if we are to better understand opportunities to slow their overexploitation (22). To this end, we comprehensively quantify and trace virtual groundwater transfers from these aquifers to their destination of final use. To our knowledge, this is the first time this has been done and represents an important first step in

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Significance

Irrigated agriculture is contributing to the depletion of the Central Valley, High Plains, and Mississippi Embayment aquifer systems. Agricultural production within these aquifer regions comprises a significant portion of the domestic and international cereal supply; thus, potential food security implications arise if production significantly decreases to bring groundwater withdrawals within sustainable limits. For the first time to our knowledge, this study tracks and quantifies the food and embodied groundwater resources from these aquifer systems to their final destination and determines the major US cities, US states, and countries that are currently most reliant upon them. Tracing virtual groundwater transfers highlights the role of distant demands on local groundwater sustainability and the fact that aquifer depletion must be considered within its global context.

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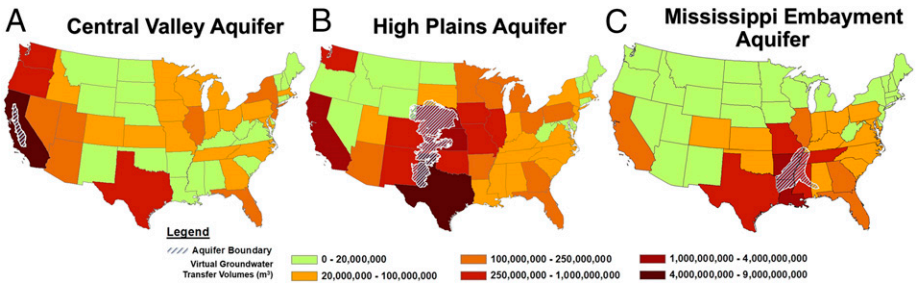

Fig. 1. Maps of overexploited aquifers in the United States: (*A*) CV, (*B*) HP, and (*C*) ME. The areal extent of the aquifers is shown with white highlighting. The US states are shaded to indicate the volume of virtual groundwater transferred from each overexploited aquifer. Darker shades highlight more virtual groundwater transfers into the US state.

the evaluation of consumption flows of critical groundwater resources. In this paper, we use high-resolution empirical data on domestic food transfers within the United States in 2007 (23, 24) and link this with port-level data on international exports (25). Additionally, we use national statistics on agricultural production (19) and irrigation (17) and modeled estimates of virtual water content (26, 27) to quantify virtual transfers of critical groundwater resources (refer to *Materials and Methods* and *SI Materials and Methods*). This approach enables us to identify the locations that are most responsible for—and currently most reliant upon—depletion of the HP, CV, and ME aquifers.

Results and Discussion

Total Virtual Groundwater Transfers. According to the US Geological Survey (17), irrigation withdrawals from the HP, ME, and CV systems totaled 23.38 km^3, 13.59 km^3, and 9.34 km^3, respectively (refer to the size of the circles in Fig. 2). Of these agricultural withdrawals, ~27% is lost to irrigation inefficiencies and return flows, and the rest is virtually embodied within crops and livestock (i.e., directly used for crop growth or livestock production). The groundwater footprint of a commodity is the volume of water that is virtually embodied throughout the production process of that commodity, which is also referred to as the virtual groundwater content [i.e., the volume of groundwater per commodity unit (*VGC*); refer to *Materials and Methods*]. Note that *VGC* varies by commodity and aquifer (Table 1). The total volume of virtual groundwater transfers (*VGT*; refer to *Materials and Methods*) across all aquifers is comparable to the capacity of Lake Mead (35.7 km^3), the largest surface reservoir in the United States. Between 45% (HP) and 58% (CV) of agricultural groundwater withdrawals that are virtually transferred are not used within the states overlying the aquifers, but are transferred either elsewhere within the United States or exported abroad. The vast majority of *VGT* remains within the United States, with 9% exported abroad.

Domestic Virtual Groundwater Transfers. The annual volume of *VGT* between states overlying the aquifers is 16.9 km^3, which is comparable to the annual average flow volume of the Colorado River into Lake Mead (~18 km^3/y). There are 7.30 km^3, 3.24 km^3, and 3.47 km^3 transferred out of the HP, CV, and ME aquifer boundaries, respectively, which remains within the United States. This equates to 4 (CV, ME) to 10 (HP) times more groundwater being transferred out of the aquifer regions to other domestic locations than is being withdrawn for local municipal and industrial purposes combined.

Urban areas are key recipients of *VGT*. Cities in California receive the largest share of domestic *VGT*: Los Angeles and San Francisco–Oakland receive 12.7% of all *VGT*. San Francisco–Oakland, Los Angeles, and Sacramento are the recipients of 40.5% of all *VGT* from the CV. To put the transfer volumes in perspective, around 3.4 km^3 of water was physically transferred in 2007 from the Sierra Nevada Mountains to Los Angeles via the Los Angeles Aqueduct system; in that same year, 1.76 km^3 of groundwater from the CV aquifer system was virtually transferred to Los Angeles solely in agricultural commodities.

The CV and ME aquifer systems both have one or two metropolitan areas that receive relatively large shares of *VGT* (Fig. 3). However, this is not the case for the HP aquifer system, where the transfers are more dispersed. This is likely because the HP aquifer system extends across much of the central United States, where there are more than one or two major cities or ports that would be viable principal consumption or transfer locations. This may also be due to the fact that cereals comprise a large share of agricultural production in the HP, which can be stored and widely distributed, compared with the large quantify of fresh items produced in the CV, such as vegetables and meat (Fig. 4).

With increased intersectoral demands for water, economic development, and climate change, water is projected to become more scarce in many locations (28). Conflicts have arisen between rural and urban areas, US states, and countries regarding renewable surface water allocations. Reallocation of water from rural agriculture to urban uses is a politically charged issue but a growing trend nonetheless (29, 30). These results demonstrate that water use in rural areas already largely serves urban areas by providing food (i.e., virtual water flows to cities through food commodities).

Fig. 1 highlights that domestic *VGT* are predominantly to population centers, wealthy areas, and between areas that are close in distance, as we would expect from the gravity model of trade (31). Because large volumes of water are virtually transferred within the United States, the socioeconomic and environmental challenges in both sending and receiving locations should be considered in future water supply discussions. Going forward,

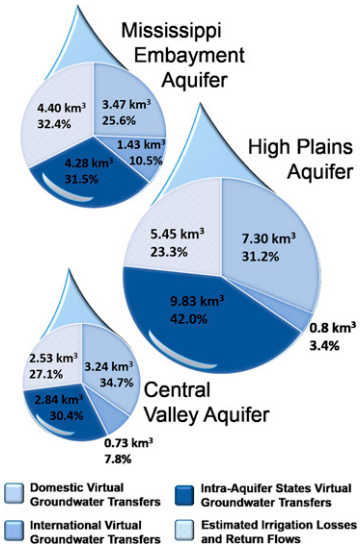

Fig. 2. Consumption of overexploited aquifers in the United States. The size of each circle indicates the volume of groundwater withdrawals for agriculture from each aquifer as given by the US Geological Survey. In 2005, 23.38, 13.59, and 9.34 km^3 of groundwater was withdrawn for irrigation from the HP, ME, and CV aquifer systems, respectively. Each circle shows the proportion of groundwater withdrawals that goes to irrigation losses and return flows, intraaquifer state transfers, domestic transfers, and international exports. The ME aquifer ships the largest proportion abroad (10.5%), compared with 3.4% in the HP and 7.8% in the CV.

Table 1. *VGC* estimates for the SCTG food commodity groups in each of the overexploited aquifers of the United States

SCTG code	SCTG name	CV, m^3/ton	HP, m^3/ton	ME, m^3/ton
01	Animals and fish (live)	1,570.7	303.7	9.0
02	Cereal grains (including seed)	271.5	68.4	129.4
03	Agricultural products except for animal feed (other)	66.2	63.9	76.5
04	Animal feed and products of animal origin	134.7	27.9	1.3
05	Meat, fish, and seafood and their preparations	1,984.7	367.4	9.9
06	Milled grain products and preparations and bakery products	107.7	47.1	369.7
07	Other prepared foodstuffs and fats and oils	246.5	164.7	57.2

Units are cubic meters of groundwater consumed per metric ton of production.

stakeholders may want to evaluate teleconnections that affect their local water balance, considering not only physical water allocations but also how water relates to the broader economy and virtual water transfers between sectors and locations.

Nearly 9% of domestic *VGT* s are to ports. This highlights the importance of food production for international export, with some states (e.g., Louisiana and Washington) exporting over half of all incoming *VGT* s. California, Texas, and Arkansas have the largest *VGT* s; the large transfer volumes of Arkansas are primarily due to large intrastate transfers of rice, which has an extremely high groundwater footprint and is widely produced in Arkansas. Moreover, 74% of all *VGT* s from the ME aquifer system originate from Arkansas and 41% of Arkansas transfers (3.21 km^3) are transported within the state for consumption, processing, and/or storage. Not coincidentally, Arkansas has seen much greater groundwater level declines than other states overlying the ME (32).

*VGT*s from Texas and Kansas are of particular interest because they are the origin of the greatest overexploitation of groundwater resources in the High Plains. Transfer volumes from Kansas were 5.66 km^3 (28.8% of HP transfers), whereas Texas had *VGT* s of 4.38 km^3 (22.3% of HP transfers). The groundwater embodied within the trade of cereals, meat, and prepared foodstuffs make up the vast majority of the groundwater transfers from these overexploited areas. Groundwater embodied within traded corn makes up the largest fraction of cereal *VGT* (96% from Kansas and 71% from Texas), beef makes up the largest fraction of meat *VGT* (98% from Kansas and 71% from Texas), and dairy products make up the largest fraction of prepared foodstuffs (57% from Kansas and 85% from Texas).

The Central Valley is often referred to as the "fruit and vegetable basket of the world" because it grows and exports an abundance of fruit and vegetables. Interestingly, we find that a relatively small fraction (i.e., 4%; Fig. 4) of *VGT* from the CV aquifer is due to trade of fresh produce. This can be partially explained by three factors. First, among the Standard Classification of Transported Goods (SCTG) (23) seven food commodity categories, the one containing vegetables, fruits, and nuts (SCTG 03, Table 1) has the smallest groundwater footprint. For example, the *VGC* of the vegetable commodity group is only 3% as much as that of the meat commodity group (SCTG 05). Second, although the CV area grows more vegetables, fruits, and nuts than other areas, it also produces and trades much of the other food commodities as well (e.g., 6 and 10 million more tons of SCTG 04 and SCTG 07 are traded than SCTG 03, respectively). Third, some produce and nuts are not represented in SCTG 03 because they are processed and included within the prepared foodstuffs trade category (SCTG 07), which, along with dairy products, make up the bulk of this category and account for 39% of total *VGT* from the aquifer.

Meat products comprise 4, 10, and 13% of traded agricultural tonnage from the CV, HP, and ME, respectively (Fig. 4); however, 38 and 31% of the total *VGT* s from the CV and HP are derived from meat products, respectively, whereas the ME only has 1% derived from meat products. The high *VGC* of feed and high proportion of cattle in the CV and HP (beef is 97% and 77% of meat *VGT*, respectively) are the primary drivers of the variances between the tonnage fraction of meat and the virtual groundwater fraction of meat. Only 30% of *VGT* s associated with meat from the ME are from beef, with the majority of the *VGT* of meat comprised of poultry and fowl, which requires ~11 times less water for production than beef; furthermore, the *VGC* of the feed is significantly smaller in the ME region than it is in the CV and HP.

Domestic food security in the United States is heavily reliant upon the unsustainable extraction of groundwater in the HP, CV, and ME aquifer systems: The cereals produced by these aquifers amount to 18.5% of the domestic cereal supply (Table 2). These groundwater resources are especially critical for agricultural production during times of drought, particularly in California (20). This buffer (i.e., option) value of groundwater (33) is not currently accounted for but will be increasingly important under a more variable future climate (34) with increased irrigation demands (35). Additionally, these aquifers provide a trade advantage to the United States, accounting for 8.6% of US cereal exports (Table 2). To protect US food security and trade interests, domestic policy makers may want to consider slowing groundwater depletion by implementing policies that recognize the full value of groundwater, such as private water markets (33), which may encourage technology adoption.

International *VGT*s. Unsustainable "blue water" [i.e., fresh surface water and groundwater (29)] sources are estimated to comprise

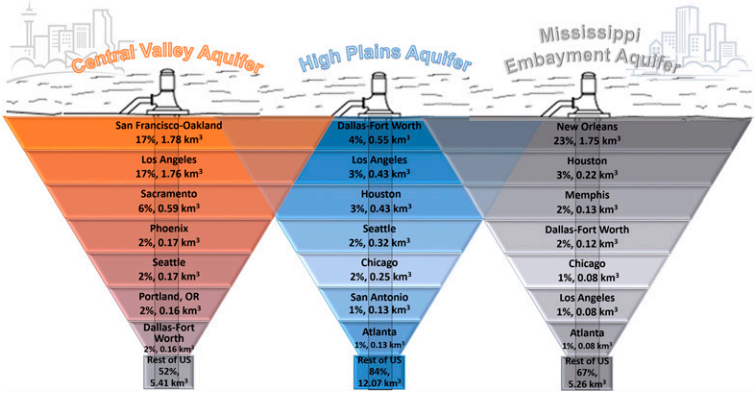

Fig. 3. Ranking of US metropolitan areas that currently most rely on virtual groundwater from each of the CV, HP, ME aquifers. The total volume virtually transferred to each US metropolitan area is provided, as well as the fraction of groundwater withdrawals from each aquifer system that this represents. Note that the triangles are provided for graphic representation only and are not scaled according to size. Importantly, cities in the western United States are relatively reliant upon virtual groundwater transfers from the CV aquifer, whereas virtual groundwater transfers from the HP aquifer tend to be more dispersed across the United States, as they are with the ME aquifer, with the exception of the major shipping port of New Orleans.

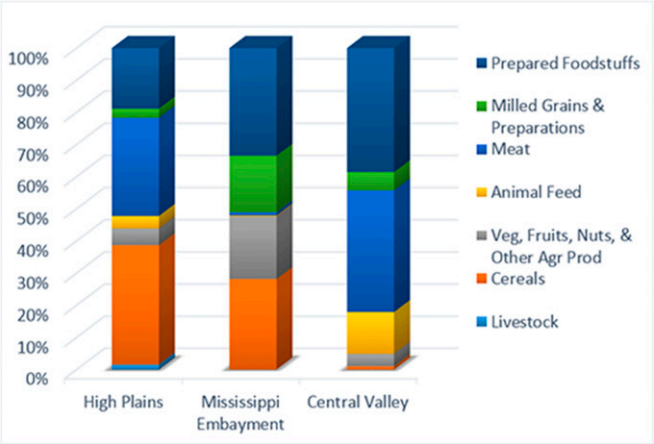

Fig. 4. Percentage of virtual groundwater transfers attributed to each of the seven commodity groups in the HP, ME, and CV aquifers.

between 32 and 52% (estimated from refs. 36–38) of the global blue water footprint of agricultural production. However, the overexploited US aquifers comprise 35% of the US blue water footprint for agricultural production. Two-fifths of global virtual blue water exports from agriculture is attributed to unsustainable water sources (calculated from ref. 36). However, only 13% of US virtual blue water agriculture exports are from the HP, CV, and ME aquifers. Therefore, the United States relies less on nonrenewable water sources for agriculture production and international export of agricultural goods than the rest of the world as a whole.

Fig. 5 shows the major international transfers of virtual groundwater from the HP, CV, and ME aquifers. Asia is the top importer of virtual groundwater from all three aquifers. Of all international *VGT*, approximately half goes to Asia. This finding parallels previous studies that show Asia as the principal importer of US agricultural goods and virtual water (26, 27, 39). Reduced agricultural production due to aquifer depletion or policies restraining groundwater withdrawals should be of particular interest to Taiwan, Japan, Panama, and Syria: They all depend on the three aquifers of this study for over 10% of their total cereal imports (Table 2).

Table 2 presents the countries that are currently most reliant upon cereals—critical for food security (e.g., ref. 40)—grown in the HP, CV, and ME aquifers. Countries are ranked in order of the fraction contribution of cereals produced with these aquifers to total domestic cereal supply (Table 2, column 4). Besides the United States itself, Taiwan is the country that is most reliant upon these aquifers; 10.0% of its domestic cereal supply is produced by these aquifers. These aquifers produce 9.2% of Japan's cereal supply and 9.1% of the cereal supply of Panama. Consumers in these countries would be affected by rising world prices if agricultural production in the HP, CV, and ME aquifer systems were to slow or halt. However, the willingness and ability of consumers to pay increased commodity prices differs across countries, such that some countries would be more affected than others.

Panama, Costa Rica, and the Dominican Republic are the third, fourth, and fifth most dependent on cereal imports from US aquifers to meet their domestic cereal requirements. However, these countries do not import large volumes of virtual groundwater because cereals have low *VGC*. Small, developing island nations, such as Cook Islands and Samoa, as well as some arid Asian countries, such as Mongolia, import relatively modest quantities of food from the US aquifers, but they disproportionately import virtual groundwater resources, because they import mostly meat and processed food commodities, which have the highest *VGC*. Agricultural land availability, soil nutrients, and industrial capabilities—rather than water—are likely restricting local production of these commodities within the island nations. Comparative advantage across a wide suite of factors leads to complexities in the teleconnected food trade system, with unanticipated outcomes, such as nonlocal aquifer depletion.

This analysis highlights international consumers that are most vulnerable to eventual reductions in agricultural production from unsustainably managed reserves of groundwater in the United States. Countries that are heavily reliant on these aquifers can use this information to evaluate how their domestic food security will be affected when agricultural production from these aquifers is eventually slowed or halted altogether. If future consumer welfare is at risk, then policy makers in those countries may want to consider diversifying the sources of their food supply, with implications for the global food trade system. Additionally, some consumers—currently not receiving a price signal of resource scarcity—may be willing to pay a premium now to store groundwater supplies for future food security. In principle, this could operate as a payment for ecosystem services (41). However, implementing the payment of such a premium may prove challenging in practice, because food commodities are available cheaply on international markets, counteracting such an exchange and instead encouraging tragedy of the commons behavior among consumers.

Concluding Remarks

It is imperative to understand the teleconnections and demand forces that are contributing to the unsustainable use of aquifers in

Table 2. Countries that are most reliant on cereals produced with groundwater from the CV, HP, and ME aquifers

Country	Domestic cereal supply, 1,000 tons	Total cereal imports, 1,000 tons	Aquifer fraction of domestic cereal supply, %	Aquifer fraction of cereal imports, %	Aquifer fraction of cereal imports from United States, %
United States	303,016	—	18.5	—	—
Taiwan	7,268	6,336	10.0	11.5	13.4
Japan	32,961	26,425	9.2	11.4	15.4
Panama	863	649	9.1	12.1	13.4
Costa Rica	1,153	1,133	7.9	8.0	8.9
Dominican Republic	2,180	1,714	5.8	7.4	8.3
Colombia	8,396	5,206	4.5	7.2	9.6
South Korea	16,401	12,660	4.4	5.7	12.0
Honduras	1,388	663	3.9	8.2	8.2
Israel	3,436	3,007	3.4	3.9	8.9
Ecuador	3,205	1,188	3.0	8.2	15.1
Syria	6,746	1,845	2.9	10.8	12.0
World total	2,120,603	345,753	2.7	2.5	8.6

Domestic cereal supply and total cereal import data (tons) were collected from the FAO (45). Countries are ranked in descending order by the fraction of their domestic cereal supply that originates from these three aquifers (column 4). Island nations that import more cereal than is required for their domestic supply have been excluded (i.e., St. Vincent and the Grenadines, Trinidad and Tobago, Grenada, Jamaica, and Barbados).

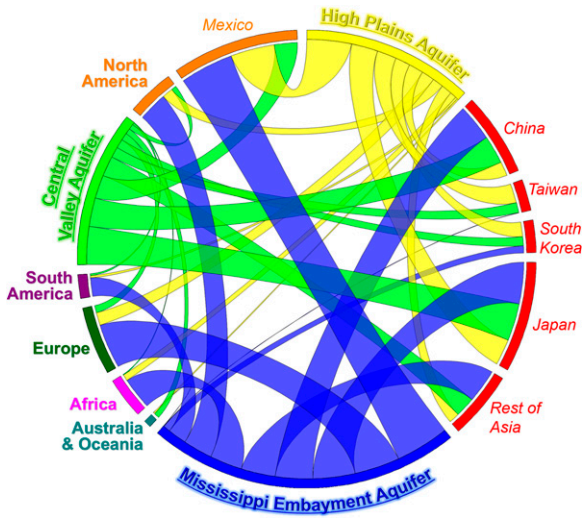

Fig. 5. International virtual groundwater transfers from overexploited aquifers in the United States. The size of the outer bar indicates the total virtual groundwater export volume for the ME aquifer (blue), HP aquifer (yellow), and CV aquifer (green). Aquifer origin volume is indicated with links emanating from the outer bar of the same color. Export destination volume is indicated with a white area separating the outer bar from links of a different color. The countries and regions that import the most virtual groundwater are provided. The links are scaled relative to the volume of virtual groundwater exported. This figure was created with network visualization software available at circos.ca, developed by ref. 44.

the United States if we are to effectively slow their depletion. In this paper we quantified and traced virtual transfers of critical groundwater resources from the HP, CV, and ME aquifers. This is the first study, to our knowledge, to track virtual groundwater transfers to the final destination using high-resolution empirical data on food commodity transfers. This is an important first step toward empowering producers, consumers, water planners, and decision makers, by linking understanding of local production withdrawals with new knowledge on the virtual transfers of groundwater resources.

The vast majority (91%) of *VGT*s remains within the United States. Cereal production using groundwater from the HP, CV, and ME aquifers contributes to 18.5% of US cereal supply and 8.6% of US cereal exports. Because these aquifers are critical to domestic food security and trade interests, policy makers in the United States may want to consider implementing policies that properly value these groundwater reserves, particularly because they may represent a strategic domestic water source in the future. Decision makers may want to reconsider current measures that exacerbate common pool aquifer depletion, and, instead, explore opportunities to value these aquifers for their risk mitigation potential under an uncertain future. A relatively small fraction of the *VGT*s are international; however, cereals produced by these aquifers comprise a significant fraction of the cereal supply of some recipient countries, such as Taiwan, Japan, and Panama. Countries that are reliant upon these aquifers can determine their potential vulnerability to global price increases associated with eventually slowing groundwater extraction in productive locations. Policy makers in these countries may consider diversifying the sources of their food supply to mitigate supply chain risk.

One unintended consequence of the current landscape of economic and trade policies has been the overexploitation of groundwater reserves in the United States. Under an uncertain climate future, in which rain-fed agriculture is likely to experience more droughts and extreme climate events, groundwater resources may become more valuable. This buffer value of groundwater—along with other nonextractive values that promote ecosystem services—is not currently incorporated into the calculation of the costs and benefits of groundwater extraction. To better determine the welfare tradeoffs and guide policy, the costs and benefits accrued along the entire value chain of this teleconnected system need to be taken into account. This includes the value of groundwater resources—both now and in the future—as a food security buffer to variable surface water supplies. Such an analysis must recognize that there are competing goals and multiple objectives related to water resources use, and that decision makers often work at spatial and temporal scales vastly different from those necessary to address global sustainability challenges.

Materials and Methods

Food Transfer Data. Data on food transfers (in tons) were collected from the Commodity Flow Survey (CFS) for the year 2007 (23). Bilateral food transfer data are provided for 123 CFS areas within the United States and for seven agricultural commodity groups [as defined by the SCTG (23)]. These commodity groups are listed in Table 1.

Port-level export data were collected from the US Census Bureau (25). Harbors of the United States were spatially linked with CFS areas (*SI Materials and Methods*). Food transfers were traced from CFS areas overlying the aquifers to US ports, and then to international export destination. Overland agricultural exports to Canada and Mexico were obtained from the US Department of Agriculture (42) because only air and vessel modes of export were provided within the ref. 25 dataset.

Virtual Groundwater Content Estimates. The virtual water content (*VWC*) refers to the total water required for crop evapotranspiration and incorporation within the product divided by the crop yield (Eq. **1**):

$$VWC = \frac{ET + IW}{CW}, \quad [1]$$

where *ET* refers to crop evapotranspiration (cubic meters), *IW* refers to water incorporated within the harvested crop (cubic meters), and *CW* refers to crop weight (tons). The *VWC* is composed of two components: green and blue *VWC*, which correspond to rainfall and surface and/or groundwater, respectively. The *ET* and *IW* of the green *VWC* is attributed to rain water, whereas the *ET* and *IW* of the blue *VWC* (*BVWC*) is from surface water and/or groundwater sources. This study focuses on the unsustainable groundwater component of *BVWC*, the *VGC*.

SCTG 02 and 03. State-level estimates of *BVWC* for items within SCTG commodity groups 02 and 03 were collected from ref. 27. Note that ref. 27 presents conservative estimates of *BVWC* because evapotranspiration only is considered and return flows are excluded. County-level irrigation withdrawals from the US Geological Survey (USGS) in the year 2005 were used to calculate the fraction of irrigation supplies from groundwater (*GF*) for each irrigated crop produced within aquifer boundaries. County-level production data (19) were used to determine a production-weighted average *VGC* across items within an SCTG commodity group:

$$VGC_{SCTG,CFS} = \frac{\sum_c BVWC_{C,CFS} \times GF_{CFS} \times P_{C,CFS}}{P_{SCTG,CFS}}, \quad [2]$$

where *VGC* refers to virtual groundwater content, *BVWC* refers to blue virtual water content, *GF* refers to groundwater fraction, and *P* refers to agricultural production (tons). Subscripts *C*, *SCTG*, and *CFS* refer to commodity item within SCTG commodity group, SCTG commodity group, and CFS area, respectively.

SCTG 06 and 07. All methods follow those of SCTG commodity groups 02 and 03, but now production-based weights are modified. Categories SCTG 06 and 07 are composed of processed and milled goods, but the production volumes of the individual products are not available. However, the product composition of SCTG 06 and 07 can be estimated based on the production of the primary crops within the CFS area that are used in the production of the processed goods. To avoid overestimating exports of virtual groundwater embodied in SCTG 06 and 07, the processed goods that require primary crops not produced within the CFS area are not given weight in the SCTG category's overall *VGC*, whereas products whose primary inputs are crops widely grown in CFS area are weighted according to production data. This approach discounts the exports of processed commodities whose primary crops are not grown locally.

SCTG 04. The feed *VGC* was calculated in conjunction with the livestock and meat *VGC*. Feed requirements per head of the primary livestock raised within the aquifer areas [i.e., cattle, equine, goats, hogs, sheep, chickens (layers and broilers), turkeys, pheasants, and quail] were collected from ref. 43. The number of livestock head produced and sold in 2007 was collected from ref. 19. The feed requirement per head of livestock was multiplied by the number of head sold to arrive at feed requirements. The amount of feed imported into the CFS area was subtracted from the CFS area's feed requirement to get the total feed that needed to

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be produced within the CFS area. The vast majority of required feed (97%) was produced locally. It was assumed that SCTG 04 consists of the same feed composition as the feed required for livestock inside the CFS area. To determine *VGC* of feed, the required tonnage of each crop within the feed composition was multiplied by its *VGC* and then summed to get the total volume of virtual groundwater of feed. The total virtual groundwater volume attributed to feed was divided by the total tonnage of the feed crops to get the feed *VGC* for each CFS area.

SCTG 01 and 05. The volume of virtual groundwater of the required feed was divided by the total tonnage of livestock to get the feed component of the *VGC* of animal production within each CFS area. The required water for drinking and for servicing of livestock (from ref. 43) was multiplied by the fraction that was taken from groundwater (17) to get the amount of groundwater used per head of each animal. This was then multiplied by the number of each animal sold in 2007 (19) to get the volume of groundwater required for drinking and servicing for each animal type. The required groundwater volume for each animal type was summed and then divided by the total animal tonnage to get the component of the animal production *VGC* within each CFS area attributed to drinking and servicing. This was added to the corresponding *VGC* of feed production to arrive at the total *VGC* for all livestock sold from within the CFS area boundaries. The *VGC*s differ between SCTG 01 and SCTG 05 because the virtual groundwater volume is divided by the live animal tonnage for SCTG 01, whereas it is divided by the edible fraction (per ref. 26) for SCTG 05. In this way, the *VGC* corresponding to SCTG 01 and SCTG 05 are weighted by the tonnage sold or butchered of each animal type within the CFS area:

$$VGC_{SCTG,CFS} = \frac{(FR_{CFS} - FI_{CFS}) \times VGC_{SCTG04,CFS}}{P_{SCTG,CFS}} + \frac{\sum_C WR_{C,CFS} \times GF_{CFS} \times P_{C,CFS}}{P_{SCTG,CFS}} + \frac{\sum_C SR_{C,CFS} \times GF_{CFS} \times P_{C,CFS}}{P_{SCTG,CFS}}, \quad [3]$$

where *FR* refers to feed requirement (tons), *FI* refers to imported feed (tons), *WR* refers to livestock water requirement (cubic meters per ton), and *SR* refers to livestock servicing requirement (cubic meters per ton). All other acronyms and subscripts follow those above.

VGTs. The food transfer data were multiplied by the virtual groundwater content to arrive at virtual groundwater transfers:

$$VGT_{SCTG,O,D} = VGC_{SCTG,O} \times FT_{SCTG,O,D}, \quad [4]$$

where *VGT* indicates virtual groundwater transfer (cubic meters), *VGC* indicates virtual groundwater content (cubic meters per ton), and *FT* indicates food transfers (tons). Subscripts *SCTG*, *O*, and *D* indicate food commodity group, origin CFS area, and destination, respectively. In this way, *VGT* volumes are tracked from aquifer areas to their final destination.

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