Chapter 16
Global Groundwater Sustainability and Virtual Water Trade

Iman Haqiqi, Chris J. Perry, and Thomas W. Hertel

1 Introduction

The overexploitation of open-access resources is a significant issue in many locations across the world, and it is caused mainly by the fact that the cost of agricultural production does not include the negative environmental externalities of resource use. One way to reduce these externalities is by imposing regulatory restrictions on the use of natural resources in agriculture. However, these regulations can reduce the competitiveness of the local agricultural sector. This may, in turn, induce new sustainability pressures on distant land and water resources. Therefore, policymakers need to carefully consider the consequences of conservation policies before undertaking them at broad scale.

Sustainability policies can have a significant impact on how agricultural production is distributed across different regions. One way of achieving sustainability is by encouraging the cultivation of water-intensive crops in areas with abundant sustainable water resources, thereby increasing agricultural activity in those regions that can best support it. However, the effect of sustainability policies on the spatial

This chapter is a slightly revised version of a paper originally published as Haqiqi, Iman, Chris J. Perry, and Thomas W. Hertel. 2022. When the virtual water runs out: Local and global responses to addressing unsustainable groundwater consumption. *Water International* 47: 1060–1084. https://doi.org/10.1080/02508060.2023.2131272.

Data availability statement: The files needed to replicate this application are available at https://gtap.agecon.purdue.edu/simple-g/

I. Haqiqi (✉) · T. W. Hertel
Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University, West Lafayette, IN, USA
e-mail: ihaqiqi@purdue.edu

C. J. Perry
Independent Researcher, London, UK

I. Haqiqi, T. W. Hertel (eds.), *SIMPLE-G*,
https://doi.org/10.1007/978-3-031-68054-0_16

distribution of agricultural production also depends on the possibility of input substitution. For instance, sustainability policies that incentivize farmers to use less water can lead to agricultural production that makes more intensive use of capital and other agricultural inputs by encouraging the adoption of new agricultural technologies. For instance, cultivating new drought-resistant crop varieties can be economically viable, even if doing so results in higher production costs, as it helps minimize the reduction in production.

In contrast to Chap. 12, which focuses on the Western United States, here we focus on groundwater withdrawals at the global level. Local groundwater restrictions can alter patterns of global production, thereby altering trade patterns and inducing changes in virtual water trade. SIMPLE-G provides an ideal framework for studying these relationships. The next section introduces the concept of virtual water, which was originally introduced by J. A. "Tony" Allan (2011).

1.1 Virtual Water

Allan's seminal insight, captured in the phrase "virtual water," was that trade in agricultural commodities was effectively the transfer of huge quantities of water from producing countries to consuming countries. For example, producing 1 kg of wheat or rice involves the transpiration of about 1000 kg of water, so the location of this production can have a significant impact on groundwater abstraction. Thus, the virtual water trade refers to the implicit flow of embodied water within traded goods and services. Allan's main interest was in the consequences of these transfers: the extent to which political stability is preserved in countries that rely on imported "virtual water" to ensure food security. This linkage has two dimensions: First, the avoidance of "water wars" as the import of virtual water makes it unnecessary to "capture" the underlying natural resource itself, and second, enhanced food security as a direct consequence of this trade. Few rulers of fragile democracies—and nondemocracies—could survive long when the shops have no bread (Dizard 2022).

1.2 Contribution

In this chapter, we explore another perspective on virtual water: Many food-exporting countries also "export" large quantities of groundwater that are "mined" from their aquifers. Stated bluntly, these nations are exporting their environment, free of charge, to food-importing countries. Applying this insight to policy evaluations by raising concerns about food security as a result of water sustainability policies will have consequences; through a set of models and calculations within a multiscale framework, we explore the impacts of a "best case" scenario in which groundwater consumption is constrained to a "sustainable" equilibrium by prudent management. What changes are likely in the local and global patterns of commodity production, and what changes in prices can be expected as a consequence of such "good governance"? SIMPLE-G offers the opportunity for a holistic approach to incorporating these spillover effects of market-mediated land and water conservation policies. This approach can provide a more accurate reflection of the impact of groundwater policies on production and land use and promote the sustainable use of resources within a comprehensive framework.

1.3 Sustainable Groundwater Use: Some Definitions

What does sustainability mean for groundwater? Groundwater systems are often highly complex, comprising multiple layers that are sometimes directly linked, sometimes partially linked, and sometimes completely independent; these layers are affected by the nature of the medium(s) through which, and in which, groundwater is stored, surface topology, land cover, lakes, rivers, and artificial interventions such as irrigation systems. Here, the objective is not to address these physical variables in detail—although in any specific case, they are fundamentally important.

The commonly adopted definition of sustainable groundwater use is that abstraction should not exceed recharge. This apparently logical formulation is at best misleading (Bredehoeft 2002); useful analysis of the status of a groundwater system—and the consequences of overabstraction—requires a rather more careful specification of the scenario being evaluated.

A groundwater system is in *equilibrium* when inflows are equal to outflows. Inflows include natural recharge from rainfall, additional infiltration of water imported via surface irrigation systems, return flows from local groundwater abstractions, and lateral inflow from surrounding hills or aquifer systems. Outflows include evaporation from wet surfaces and capillary rise, transpiration by plants, lateral flows toward streams or surrounding aquifers, and pumping. When these two sets of flows are equal, the water table remains essentially constant when observed over a period of years, with seasonal and annual variations due to, for example, actual rainfall patterns, and associated pumping rates. Yet even from this simple formulation, we immediately see that any increase in net abstraction from an aquifer (e.g., by introducing a new tube well) must have implications for one or more of the outflows. The water table must reach a new equilibrium at a lower level at which one or more outflows are reduced—lateral outflows to streams, water consumption by natural vegetation, flows to surrounding aquifers, or evaporation from waterlogged soil. When this has happened, inflows and outflows again equate, and stability is reestablished.

Already, the definition of "sustainable" becomes more complicated than is implied by the simple rule that abstraction should be less than recharge. (Indeed, if abstraction is less than recharge, the water table will rise over time.) In the example just described, *equilibrium* is restored after an increase in abstraction; again, the observed status of the groundwater system will remain constant over a period of years. Yet the impacts of the reduced outflows to vegetation and local streams may cause damage to downstream wetlands or aspects of the natural landscape that were previously supported. Environmentalists might well argue that these are not "environmentally sustainable" outcomes, as generally interpreted; rather, they are a new, less desirable, equilibrium. Downstream users (e.g., irrigators, fishermen, and ferry operators) will have similarly negative views of the new "sustainable" scenario.

As the process of increased groundwater demand for irrigation and other sectors unfolds, we pass through a continuum of equilibria, each of which meets the stability test where inflows are equal to outflows (see, e.g., Chinnasamy and Agoramoorthy 2016). Eventually, all the natural outflows fall to zero, and incremental abstraction is supported by a continuous reduction in aquifer storage—a scenario that is literally "unsustainable" because eventually the aquifer will be depleted, salinized, or otherwise rendered unfit for use. During this stage, there are no points of equilibrium. The water table continues to fall until the final equilibrium eventually arrives: The aquifer is depleted to the point at which use is restricted to whatever recharge still, sporadically and unpredictably, reaches the saturated zone. The "mining" element, in this scenario, necessarily reduces to zero.

Why is this more complex perspective on "sustainable" groundwater use important? It is commonplace to report that because measured abstraction is less than recharge there is "net availability" of groundwater for development (see, e.g., Chatterjee and Ray 2016). This position is apparently based on the assumption that the "available" resource is currently disappearing somewhere; such a conclusion is rarely (never?) associated with a reportedly *rising* water table. Alternatively, it might be assumed that the outflows that are impacted by further abstraction have no value. In this phase of development, the properly evaluated "sustainable" yield is or should be a *political* decision based on trade-offs among alternative water allocation regimes; as such, it is an issue of governance to which information (e.g., measurements, observations, and modeling) contributes to political decisions that determine allocations. Here, we include in the spectrum of possible political interventions the decision to do nothing, thereby allowing the tragedy of the commons (Hardin) to unfold. To our knowledge, this policy has never been made explicit, but this scenario is not rare. Before 2014, California's aquifers were being used excessively and without regulation. However, following the introduction of the Groundwater Sustainability Act, the Groundwater Sustainability Agencies were required to take up local control. They gradually implemented regulations, bringing 98% of Californians under their umbrella. Despite challenges, this has been a significant step toward securing California's groundwater resources.

In fact, all water resource development (e.g., diversion from rivers, construction of dams, water harvesting, deforestation, reforestation, and conversion to new irrigation technologies) involves some degree of reallocation of water among users and uses. Food security and rural employment increase when irrigation water is diverted from estuaries and wetlands. While such developments have vastly increased food production and hence have benefited society generally, they are not without costs; it is the role of governments, through political processes, to evaluate the underlying trade-offs and intervene appropriately.

In sum, groundwater development has four stages: (1) the natural state of precipitation, vegetation, and runoff; (2) progressive human interventions that expand use (e.g., agriculture and domestic water supply) at the expense of other outflows while maintaining equilibrium between inflows and outflows; (3) groundwater mining, where outflows exceed inflows and the aquifer is progressively depleted; and (4) effective depletion of the aquifer, often associated with (a) subsidence of the land surface, which in many areas is already ongoing and substantial (Galloway and Burbey 2011); (b) soil compaction, such that infiltration is restricted and storage of soil moisture in the profile is reduced; and (c) extended time for any infiltration to reach the saturated zone, due to a combination of soil compaction and the ever-increasing depth to the water table. Unfortunately, many aquifers around the world are in the third stage of progressive depletion; in the absence of interventions by the relevant authorities, they will automatically progress to the fourth stage, effective depletion, and irreparable damage.

In this chapter, we assess the impacts of restricting groundwater abstraction to sustainable levels—halting the "mining" of groundwater and returning to stage 2, maintaining equilibrium between inflows and outflows. This intervention results in the redistribution of production and trade and associated local and global price changes. Achieving this goal would constitute improved governance, requiring interventions by the relevant authorities to reduce groundwater abstraction in many areas by defining allocation policies, introducing laws that reflect those policies, and providing institutional arrangements to enforce those laws.

These interventions will be politically challenging, and some countries will fail. In the following analysis, we attempt to evaluate the local and global economic costs associated with this move to "good governance." Such governance would allow for continued, controlled use of aquifers as temporary buffer storage and preservation of resources that can be assigned to priority uses during periods of severe drought. The alternative of allowing aquifer depletion and loss of buffer function will undoubtedly be far more costly—an issue to be addressed in a further study.

1.4 The State of the World's Groundwater

Various analysts have assembled data and models to assess groundwater status globally and for major regions (Siebert and Döll 2008, 2010; Wada et al. 2012, 2014; Famiglietti 2014). While estimates vary depending on the methodology and the time period analyzed, there is consistency among all analysts that current irrigation in major agricultural areas is dependent on groundwater abstraction rates that deplete the underlying aquifers.

In addition to these concerns, the rate of increase is remarkable. According to Wada et al. (2014, p. 14), "the current degree of non-sustainable use may compromise the future livelihoods of millions of people and their living standards": Global aquifer depletion almost tripled between 1960 and 2010 and is projected to almost double again by 2099 (although whether these quantities of water actually exist must be questioned). Among individual countries, the increased rate of depletion between 1960 and 2010 was most pronounced in India (almost tripling) and the United States, China, and Pakistan (roughly doubling). In Saudi Arabia, fortunately, an outlier, consumption increased sixfold—mostly due to the now-abandoned policy of pursuing self-sufficiency in wheat, but abstraction is still driven by substantial production of irrigated fodder. According to Famiglietti (2014, p. 948), “vanishing groundwater will translate into major declines in agricultural productivity and energy production, with the potential for skyrocketing food prices and profound economic and political ramifications.” The next sections address the likely impacts—locally and globally—of the reductions in water supply that would stabilize aquifers.

2 SIMPLE-G Version Employed in This Chapter

To capture the local, national, and global impacts of and responses to sustainability groundwater restrictions, we employ a globally gridded version of SIMPLE-G that contains around 1.3 million grid cells at a resolution of 5 arcmin, comprising squares with a width of 9.26 km at the equator. As in the SIMPLE-G-US model used in Chap. 12, each grid cell represents a distinct unit of agricultural production on which competition for land and water resources plays out within and between rainfed and irrigated crop production. It also includes differentiated markets at subregional and grid-cell levels. In the face of groundwater sustainability restrictions, the model solves for the gridded equilibrium level of irrigated and nonirrigated land as well as for the extraction of groundwater and surface water for crop production. It also determines the new equilibrium for local, national, and global crop prices and for domestic use and international trade in crops.

The production at each grid cell follows a nested Constant Elasticity of Substitution functional form as detailed in Fig. 16.1. This figure illustrates how various agricultural inputs are combined, reflecting the imperfect substitutability between them. Specifically, groundwater, surface water, and irrigation equipment are first combined into a composite “water input.” This composite water input is then combined with land to form “augmented land.” Finally, all remaining inputs are grouped into a single category, with a distinct representation of labor demand.

2.1 Product Differentiation

The SIMPLE-G model does not model individual farmers’ behavior but rather depicts the outcome at the aggregate level in each grid cell for all crops aggregated into a single composite commodity. The crop output of each grid cell is differentiated from that of other grid cells, reflecting differences in crop composition. This product differentiation applies at both the national and regional levels. The SIMPLE-G model used here has 17 consumption regions (derived from SIMPLE, see Part III)

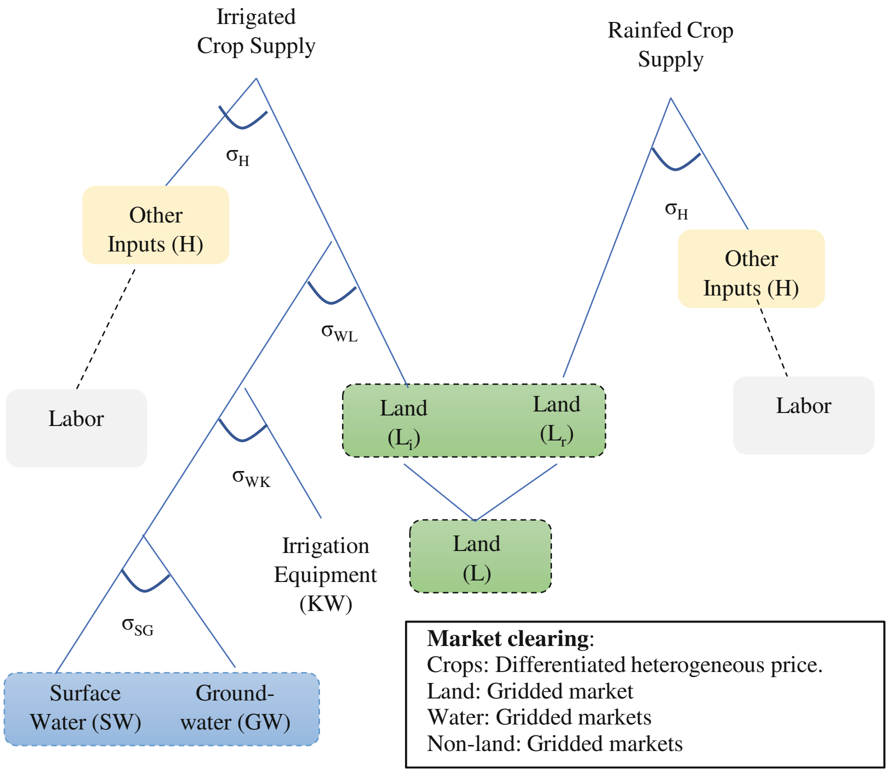

Fig. 16.1 Overall gridded production structure of the SIMPLE-G model The model determines the equilibrium local prices, land use, water use, and agricultural demand and supply for other inputs, including labor

and 136 subregions, of which 120 are individual countries. In any given grid cell, yield, water use, and nitrogen fertilizer use in crop production are weighted averages over all crops. However, we distinguish between rainfed and irrigated crop production within each grid cell.

2.2 *Virtual Water Trade*

This version of SIMPLE-G introduces virtual water trade to represent the water embedded in the international trade of agricultural commodities. There is a rich body of literature around the concept, applications, and modeling of virtual water trade (Allan 1997, 2003, 2011; Dalin et al. 2017; Rosa et al. 2019). Here, changes in virtual water trade are distinguished by source, and these changes follow the corresponding changes in local production and regional exports (Haqiqi et al. 2022).

2.3 Labor Market Outcomes

In light of the findings in Chap. 13, we add labor market outcomes to this version of SIMPLE-G. It is crucial to consider the effects of sustainability policies on the labor market, especially for farm workers. Sustainability policies can have a range of impacts on the labor market. Certain sustainability policies, such as those that target labor-intensive agricultural activities, can result in job loss. Farmworkers are particularly susceptible to this because the agricultural sector already relies heavily on mechanization and new technologies. On the other hand, some sustainability policies can create new jobs. However, farm workers may not have the skills or resources to make the sectoral or geographic transition to these new jobs. Here, we add a simple model of labor employment in crop production without explicitly modeling movement across economic sectors. In this version, the labor market follows the composite of human system inputs. The mobility and rigidity of the farm labor force are spatially heterogeneous and informed by travel time datasets.

3 Experiment Design

To focus our analysis on the impact of groundwater sustainability restrictions, we assume no changes in regional population, income, or biofuel demands. However, the demand responses to changes in food prices are captured in the interaction of demand and supply in the regional and global markets. Additionally, we assume no change in local climate conditions; this assumption allows us to assess the impact of groundwater restrictions taken on their own.

3.1 Groundwater Restriction Scenario

To permit a unified analysis of groundwater sustainability policies, we pair information from a hydrological model with the SIMPLE-G-Global model (Fig. 16.2). Several studies have successfully linked these two models (e.g., Woo et al. 2022), shedding light on the impacts of surface water scarcity (Liu et al. 2017) and the yield impacts of compound hydroclimatic extremes (Haqiqi et al. 2023). Here, we follow Grogan et al. (2017a, b) and employ the outputs of the water balance model (WBM), a validated and widely used macroscale hydrological model (Wisser et al. 2010; Grogan 2016; Grogan et al. 2022). Consumptive water requirements are calculated by crop and growth stage based on soil moisture, temperature, and irrigation status. The sources of irrigation in the WBM can include reservoirs, rivers, shallow groundwater, and nonrenewable groundwater if available. The model also considers nonbeneficial consumption and return flows through irrigation runoff, baseflow between groundwater and surface water, and percolation of irrigation return flows

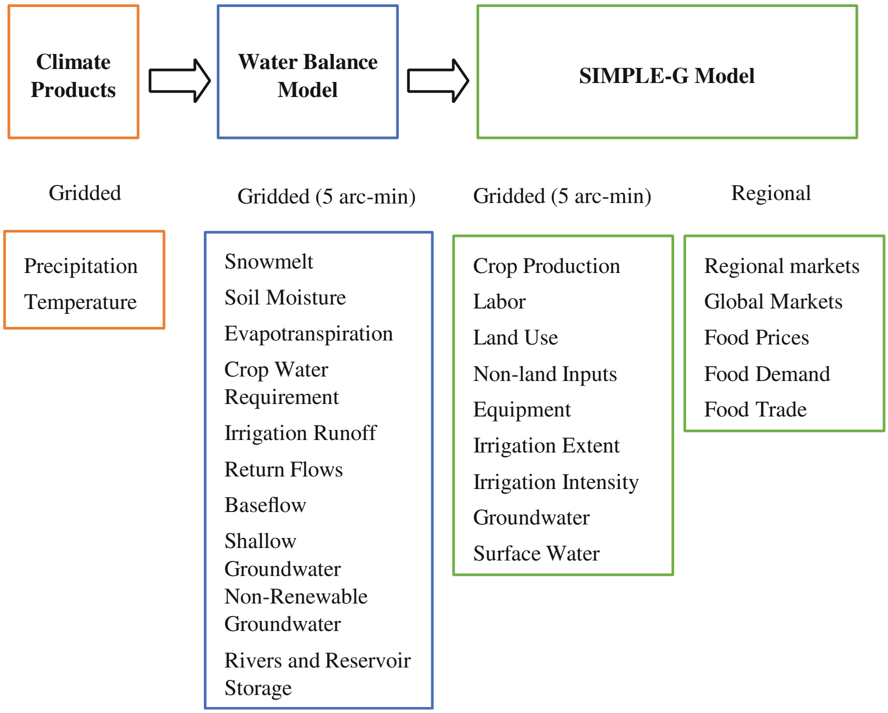

Fig. 16.2 Employing hydroclimatic information to inform the economic model about irrigation water availability and nonrenewable groundwater irrigation The water balance model (WBM) is a global gridded framework for modeling water mass balance for each grid cell. It simulates the vertical water exchange between the atmosphere and land as well as the horizontal flow of water through river networks, baseflow, and runoff. Daily precipitation and temperature data from climate products and information regarding agriculture and water demand at each location are used as inputs for the WBM. The simulated changes in surface water and groundwater volumes are fed into the SIMPLE-G model, which models decisions about land and water use. The regional outcomes are determined via the interaction of gridded crop outputs and regional and global market responses

to shallow groundwater. The multiscale nature of this model, which builds from the grid cell to global hydrology, makes it appropriate for this study.

We follow Grogan et al. (2016, 2017a, b) to determine the sustainable level of groundwater abstraction, determining the maximum allowable level of groundwater use such that there is zero nonrenewable groundwater use, thereby ensuring a stable equilibrium level of groundwater. For each grid cell, we calculate the required reduction in abstractions to achieve this objective. This level is calculated by running the WBM over the period from 1980 to 2009, while not allowing abstraction from nonrenewable resources. The sustainable level of abstraction varies each year depending on weather conditions. To avoid excessive complexity and in order to focus on long-run conditions, we take the 30-year long-term average as the basis for determining the sustainable level of abstraction. We utilize historical global observational climate products based on ERA-interim (European Centre for Medium-

Range Weather Forecasts-reanalysis, Dee et al. 2011), MERRA (Modern-Era Retrospective Analysis for Research and Applications, Rienecker et al. 2011), NCEP (National Centers for Environmental Prediction, Saha et al. 2014), and UDEL (University of Delaware, Willmott and Matsuura 2001). The 30-year average sustainable level of abstraction is used to inform the economic model about long-run groundwater availability. There are other possible definitions of sustainability, and we will discuss the implications of this choice below.

3.2 Interoperability and Consistency

Interoperability refers to the ability of different models to communicate and exchange data with each other. In multisystem analyses of agriculture that involve hydrology and climate, interoperability is important because it enables researchers to combine different datasets and model insights, resulting in more comprehensive and realistic simulations of the complex interactions among agriculture, climate, and other systems. It is crucial to ensure temporal and spatial consistency of the exchanged information, and this is often challenging when it comes to combining economic and biophysical models.

One challenge we face is that SIMPLE-G-Global is constructed based on economic and agricultural information circa 2017. In other words, crop production, cropped area, yields, and prices reflect more recent market conditions than are reflected in historical weather data. In addition, the size of SIMPLE-G grid cells is 5 arcmin, while the historic WBM runs are for global 30 arcmin grid cells. Having determined the long-run historic sustainable level of groundwater withdrawal by grid cell, we take the current conditions of water resources based on recent WBM runs from 2012 to 2018 based on GLEAM v3 (Global Land Evaporation Amsterdam Model, Martens et al. 2017), which uses 5 arcmin grid cells. This allows for consistency with the 2017-based economic model. We assume that all the smaller (5 arcmin) grid cells follow their underlying larger grid cells in terms of nonrenewable groundwater rates. For this study, we reconstruct the SIMPLE-G global model based on the WBM land use and land cover dataset.

Table 16.1 summarizes the current situation for a set of major groundwater users in the world. Overall, 27% of total irrigation water consumption is linked to nonrenewable resources. However, this is substantially higher in some regions—62% in Iran and 39% in India. Compared with total global crop water demand, the nonrenewable groundwater contribution is around 6% (although this figure is 43% for Iran and 23% for India). The outputs of the WBM in terms of groundwater and surface water use in crop production are in line with those of other studies (Siebert and Döll 2010; Chapagain and Hoekstra 2011; Gleeson et al. 2012; Bierkens and Wada 2019; Mekonnen and Hoekstra 2020).

Figure 16.3 shows the distribution of the cropped areas that rely on irrigation groundwater around the year 2017. “Green” water is that provided to crops by rainfall; “blue” water comprises irrigation water from surface and groundwater.

Table 16.1 Total crop water demand and contribution of nonrenewable resources for major groundwater users circa 2017

	Total crop water demand	Green water contribution		Blue water contribution		Nonrenewable groundwater	
	(km^3 year^{-1})	(km^3 year^{-1})	%	(km^3 year^{-1})	%	(km^3 year^{-1})	%
India	493	203	41	289	59	112	23
China	438	223	51	215	49	64	15
Pakistan	101	2	2	98	98	21	21
US	428	374	87	55	13	13	3
Iran	6	2	31	4	69	3	43
Mexico	48	36	76	12	24	3	5
World	3,848	2,934	76	915	24	244	6

Source: Outputs of the global water balance model based on GLEAM v3. Aggregated from 5 arcmin grid cells. Authors' calculations are based on Grogan (2016) and Grogan et al. (2017a, b, 2022). The percentage values show the share of total crop water consumption

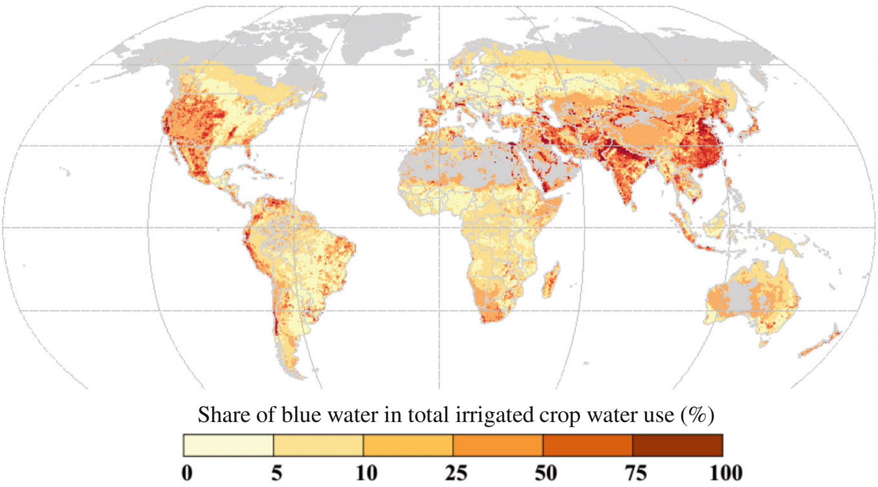

Fig. 16.3 Spatial distribution of irrigation showing the share of blue water in total gridded crop water consumption around the year 2017 *Red* indicates that little green water is available to crops. Therefore, if there is crop production in these locations, the area must be irrigated

Figure 16.4 shows groundwater hotspots across the globe. These are most prominent in the United States, China, India, Pakistan, and the Middle East, where crop water demand in some grid cells is obtained almost entirely from nonrenewable resources. As seen here, the problem of nonrenewable groundwater abstraction tends to be quite concentrated.

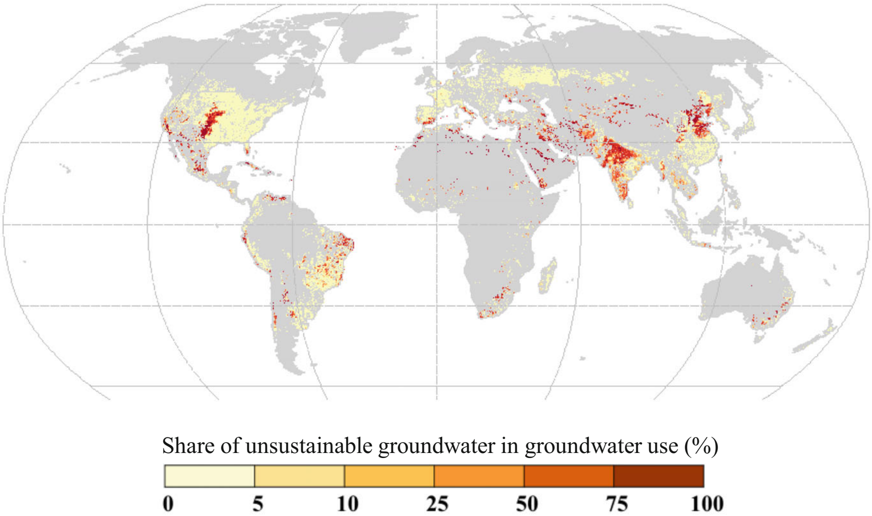

Fig. 16.4 Spatial distribution of unsustainable groundwater illustrating the share of unsustainable groundwater in total gridded irrigation water consumption around the year 2017 *Red* indicates that crop production relies mainly on unsustainable groundwater. *Gray* indicates areas not irrigated

3.3 Implementing Groundwater Restrictions in the SIMPLE-G Model

As discussed previously, the groundwater sustainability limits are calculated by the WBM considering the hydrological relationships and connections within and across grid cells. To allow for a deeper understanding of the distinct forces at work when groundwater sustainability restrictions are imposed, we first run the SIMPLE-G model assuming no change in surface water use, irrigation intensity, or irrigation extent. This restricted scenario generates the largest possible impacts on food prices and food consumption.

While informative, this simplified scenario does not capture adaptation to the sustainability policy, nor does it capture spillover effects. Therefore, we consider additional scenarios in which the system responds to these direct impacts. The first line of response involves a change in the composition of irrigation water resources. Depending on availability and relative costs, the model measures the change in surface water withdrawals as cost-minimizing producers attempt to reduce the impacts of groundwater restrictions on production. Then, the model considers changes in irrigation intensity in terms of the water supplied and used by crops. At the level of a grid cell, this can be due to a change in the composition of crops within the grid cell or it can reflect a shift to a different deficit irrigation strategy that is not explicitly modeled. All these changes can affect the rate of groundwater recharge and thus alter the initial sustainability limit. These changes also have implications for downstream surface water availability. To capture the downstream effects, we include another sustainability scenario with iterations between the SIMPLE-G economic model and the WBM hydrological model. In this scenario, decisions regarding surface water, irrigation intensity, and irrigation extent are transferred to the WBM, which then provides implications for surface water availability downstream and a revised required change in groundwater restrictions. We will show why these return flows are important for determining the spatial pattern of production at the local level.

4 Results

Restricting groundwater consumption alters global agricultural production. If there are no other sources of water, which is the case for many hotspots of unsustainable groundwater abstraction, the immediate direct impact is a fall in production. According to our calculations, the consequence of this "first round" of responses to the groundwater sustainability restriction is a 12.3% reduction in global crop production (around two billion tons of corn-equivalent crops). Despite comprising only 6% of global water consumption, the proportionate reduction in production is twice as large due to the relatively high productivity of groundwater. However, as the food system responds to this groundwater constraint, the final impact on global crop production is greatly moderated and limited to only −0.2% corresponding to a change of −28.4 million tons in corn-equivalent crop production.

Figure 16.5 decomposes the change in global crop production due to groundwater sustainability restrictions. We label them as follows: "no adaptation" (the direct effects), "substitution" of surface water, "rainfed conversion," "relocation," and "global trade." The initial margin of adjustment involves substituting surface water for groundwater, where feasible, and utilizing other farm inputs more intensively (bar b). This adaptation results in a 3.5% moderation in the global crop output decline. The next farm-level response considered is the conversion of irrigated land to dryland crop production, where rainfall is adequate. Despite rainfed production having a lower yield (or simply not being possible in some locations), in the aggregate, these results suggest that rainfed substitution can offset one-third of the damage at the global level (a 3.18% increase in Fig. 16.5, bar c). The consequences of conversion from irrigated to rainfed crop production depend on the relative yields, changes in local land rents, and the demand for alternative land uses. The next margin of response in Fig. 16.5 (bar d) is due to the national relocation of production. Rising prices in countries where groundwater is restricted motivate the expansion of production in other suitable locations, especially in regions with strong, price-inelastic, domestic demand (e.g., South Africa, India, and China). The extent of expansion in other grid cells depends on biophysical and economic conditions in each grid cell, but at a global level, these adjustments offset about one-sixth of the direct impact (2.1% increase in Fig. 16.5, bar d). Similarly, international trade in agricultural production offsets the initial fall in production through exports and imports and the ensuing trade in "virtual water." (Bar e offsets 3.3% of the global

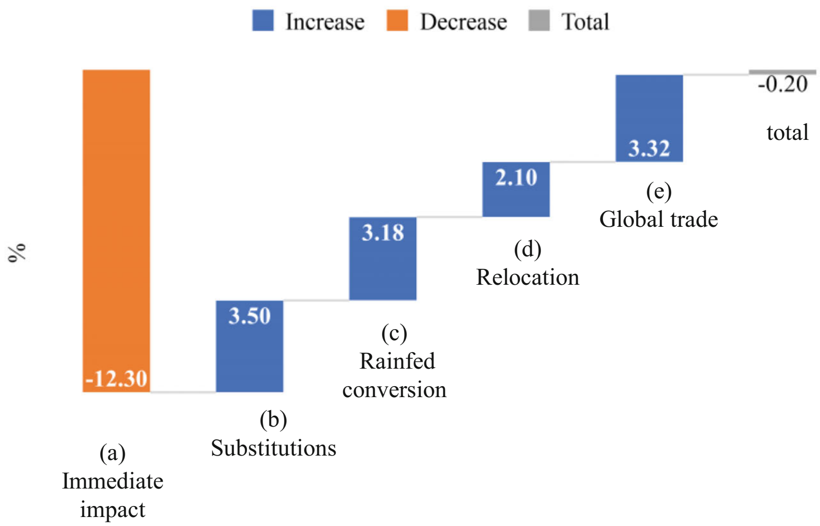

Fig. 16.5 Decomposition of global crop response to global groundwater sustainability restrictionsThe leftmost (*red*) bar shows the immediate/direct impact prior to adaptation. The subsequent bars incorporate successive market-mediated adaptations: (**b**) substitution of surface for groundwater as well as other economic responses by farmers, (**c**) conversion of irrigated to rainfed area, (**d**) expansion of domestic production in response to higher prices, and (**e**) price-induced expansion in other regions

production decline). Depending on and product similarity and trade flexibility, the contribution of relocation can increase to 4.5% while trade contribution may decline to 1.9%. See the application files for different closures. Columns 2 and 4 in Table 16.4 provide more detail on the change in virtual water trade due to the groundwater sustainability policy.

At the global level, implementing the sustainability policy implies a 27% reduction in groundwater consumption (244 km^3), corresponding to a 6% fall in total water consumption in agriculture from all sources (rainfall, surface water, and groundwater). Due to multiscale responses, the long-run impact on crop prices is quite modest (0.4%). However, the price increases are much larger in some local markets. The analysis projects a long-run increase in global surface water withdrawal of 3.42%. On the other hand, despite the fact that global irrigated production has declined by 1.03% (−68 million tons), rainfed production has increased by 0.42% (+39 million tons). This nearly offsets half of the global reduction in irrigated output. This is also reflected in the cropped area: changes of around −0.43% in the irrigated area (−1.4 million ha) and + 0.21% in the rainfed area (+2.6 million ha), leading to an increase in the global cropped area of 0.08% or + 1.2 million ha (Table 16.3, columns 2–8).

The long-run production impacts are small at the country level, as similar adaptations can occur within a country. The findings suggest that in China, India, the United States, Pakistan, and Iran, the total annual production will decline by −12.5, −6.0, −3.0, −2.6, and −2.1 million tons of corn-equivalent crops, respectively. Additionally, the overall long-run employment impacts are positive for many countries. According to the model output, China, India, Indonesia, Bangladesh, and Turkey will experience 296.6, 236.9, 66.7, 57.5, and 34.6 thousand new agricultural jobs, respectively, due to spillovers and expansions in croplands. The largest negative employment effects are in Pakistan and Vietnam, where crop employment falls by −36.0 and −24.8 thousand jobs, respectively.

4.1 Spatial Distribution of the Impacts

This section illustrates the final changes in the equilibrium levels of input demand and crop supply in response to the global enforcement of sustainable groundwater use. These are equilibrium outcomes of the model and reflect interactions between local and global agricultural markets. The spatial heterogeneity of the impacts is due to both heterogeneity in the magnitude of the reduction in groundwater and biophysical differences across locations. The findings suggest a significant change in the pattern of irrigated production, water consumption, irrigated cropped area, and employment in irrigated agriculture as a consequence of the sustainable groundwater policy.

4.1.1 Impact on Cropped Area

Figure 16.6 shows the spatial distribution of the impact on cropped areas. Red and yellow indicate contraction, and green indicates expansion as a percentage change. The grid cells with a high dependency on unsustainable groundwater would face a sharp reduction in irrigated cropped area, coupled with an increase in rainfed cropland. The net change for such areas—which include California's Central Valley, the US Ogallala Aquifer, the Mississippi River Basin, parts of India and Pakistan, parts of China, North Africa, and the Middle East—is a decline in cropped area. The analysis projects a slight increase in both irrigated and nonirrigated areas for the rest of the world.

4.1.2 Impact on Surface Water

Figure 16.7 shows the spatial distribution of the impact of the groundwater conservation policy on surface water irrigation as a percentage change. Surface water irrigation increases in almost all irrigated areas, with the greatest increases occurring in the hotspots of nonrenewable groundwater use. As this is a percentage change, the magnitude of the change in surface water irrigation depends on availability and current uses. The increase in surface water irrigation reflects the substitution of

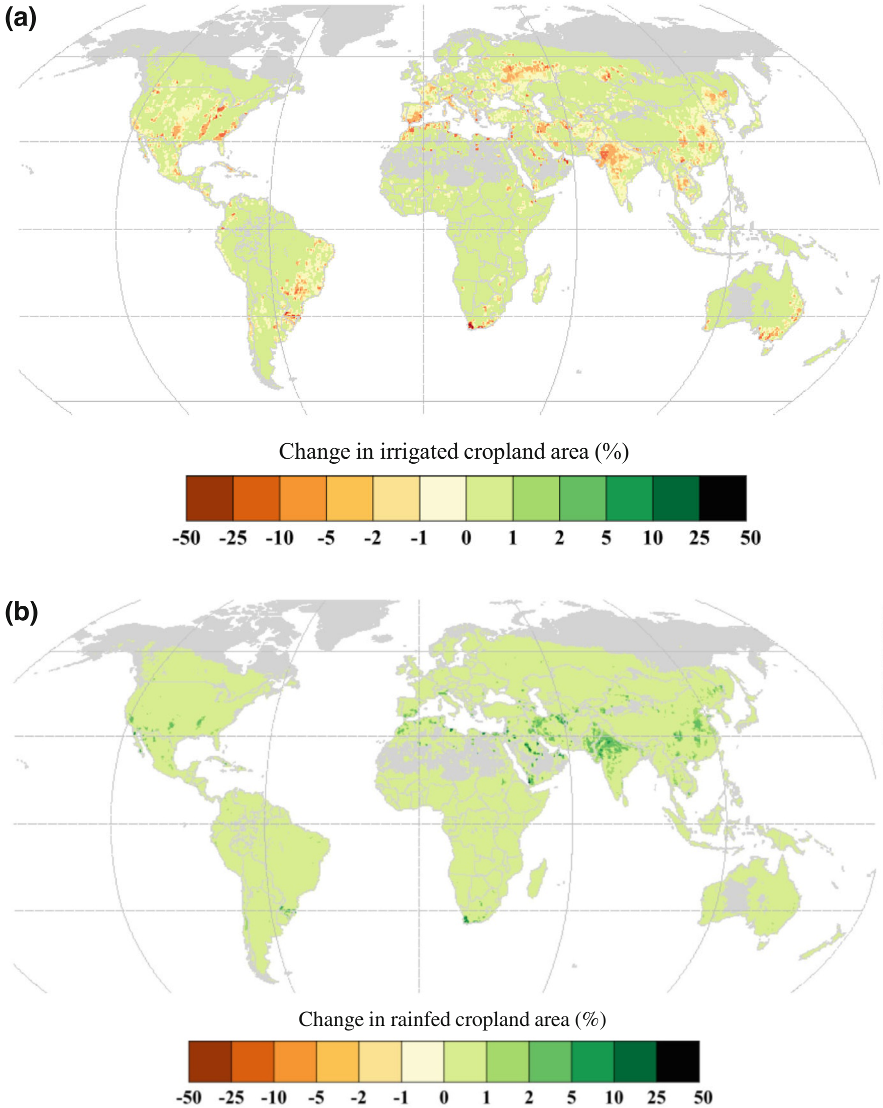

Fig. 16.6 Percentage change in (**a**) irrigated and (**b**) rainfed cropped areas in response to global groundwater sustainability restrictions produced by the water balance model

groundwater or a change in the location and scale of production. These changes can be decomposed into a "substitution effect" and a "scale effect." If the substitution effect is dominant, the percentage change in surface water use in the targeted areas is positive and more than compensates for the decline in irrigated areas. If the scale

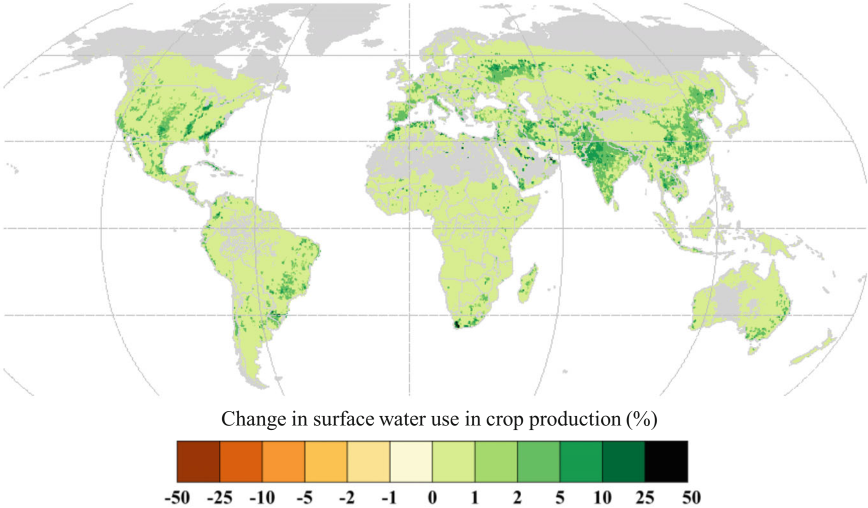

Fig. 16.7 Global changes in surface water irrigation in response to global groundwater sustainability restrictions The map shows the percentage change in surface water use in irrigation. The impact on surface water can be decomposed into a "substitution effect" and a "scale effect." If the substitution effect is dominant, the change in surface water use in targeted areas is positive and compensates for the decline in irrigated areas. If the scale effect is dominant (less irrigated area), the change in surface water use in the targeted area is negative. Dark green indicates an increase in surface water use with a dominant substitution effect, and light green indicates the locations with an increase in surface water irrigation due to a positive scale effect, absent the substitution effect

effect is dominant (i.e., less irrigated area overall), then the change in surface water use in the targeted area is negative. (Haqiqi et al. (2022) explore the extreme case in which the expansion of surface water irrigation is restricted in targeted areas.)

The maps illustrate the conversion to rainfed production in targeted locations: A clear increase in rainfed areas is projected for most of the grid cells, with large reductions in irrigated areas. Both maps show a moderate increase in irrigated and rainfed areas (*light green*). The expansion in global cropland area and conversion to rainfed production are important channels of adjustment and economic responses to groundwater sustainability policy.

4.1.3 Impact on Production

Figure 16.8 illustrates the impact of enforcing sustainable groundwater use on equilibrium irrigated and rainfed crop production. These changes are the consequences of the changes in water use, land conversion, employment, local rents, crop prices, farm revenues, and other local and global changes. In general, irrigated production declines in hotspots with unsustainable groundwater use, while rainfed production increases. The increase in surface water use in some dry locations may

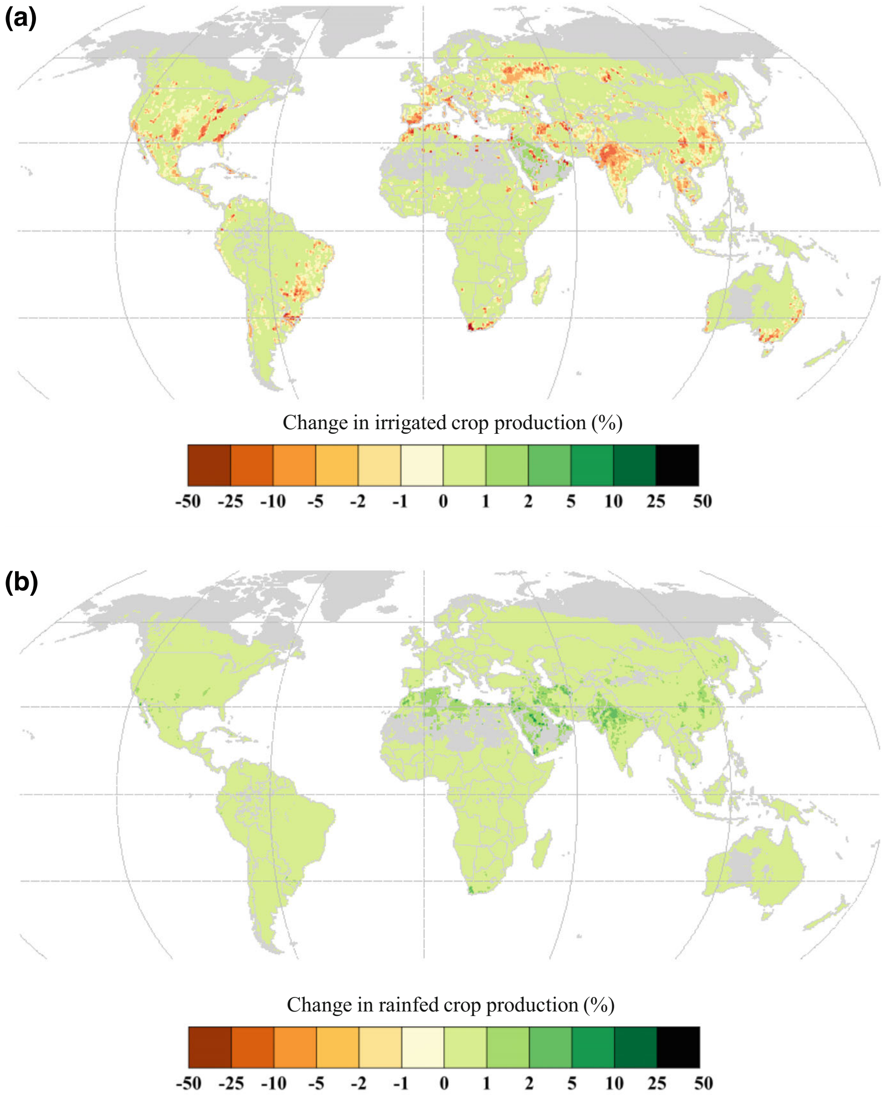

Fig. 16.8 Percentage change in (**a**) irrigated and (**b**) rainfed crop production in response to global groundwater sustainability restrictions *Red* and *yellow* areas indicate a reduction in production and *green* areas indicate an increase in production. While irrigated production in the unsustainable groundwater hotspots is substantially reduced, these hotspots also show the biggest percentage increase in rainfed production. This conversion to rainfed agriculture compensates for some of the immediate impacts on irrigated production. In addition, *light green* on the irrigated and rainfed maps indicates an expansion of crop production in nontargeted locations. While the patterns are similar to changes in the cropped area, the percentage change in production is smaller because rainfed crops have lower yields

cause an increase in irrigated production next to the targeted areas or may not be enough to recover irrigation production (e.g., in the Middle East).

4.2 Regional Outcomes

Restricting groundwater irrigation has diverse implications for regional crop production, land use, and food prices. Table 16.2a reports the long-run results at the regional scale, and Table 16.2b reports the absolute changes. In terms of percentage changes, the largest price increases arise in the Middle East, North Africa, and South Africa. In general, rainfed production increases, while irrigated production declines. In countries facing less severe restrictions, conversion to rainfed and surface water-fed cropping (driven by higher local prices) can fully offset the decline in irrigated production.

In absolute terms, the biggest declines in crop production are predicted in China, India, the Middle East, and North Africa, where crop production will decrease by −12.5, −8.8, −3.6, and −2.5 million tons, respectively.

4.3 Implications for Virtual Water Trade

Groundwater restrictions are expected to alter agricultural trade patterns (Table 16.3). The biggest percentage change in agricultural trade flows is expected for North Africa, South Africa, and the Middle East, where production is sharply reduced and imports rise. The model suggests that trade will play an important role in meeting the demand for food in these regions. (Table A6 in Haqiqi et al. (2022) reports country-level results.) The largest percentage declines in production are estimated to occur in Saudi Arabia, Jordan, South Africa, Oman, and Iran, where production drops by 19.0%, 10.5%, 7.6%, 4.8%, and 2.8%, respectively (see Haqiqi et al. 2022, Table A6). In these countries, there is little possibility of using surface water as a substitute for groundwater (indeed, rivers in these areas are often overabstracted), and there is little room for expanding rainfed agriculture at competitive production costs. On the contrary, production is expected to increase in Turkey by 1.7%, as access to more land and water is less challenging. In larger countries such as India, China, and the United States, the relocation occurs predominantly within the country (Fig. 16.6).

Table 16.4 shows the impacts of groundwater sustainability restrictions on virtual trade in blue water. For all the regions listed in this table, exports of virtual blue water decrease, with the biggest declines occurring in the United States and South Asia. Note that this is largely due to the expansion of rainfed agriculture, both through conversion from irrigation and from cropped area expansion. Expanding rainfed crop production likely leads to a rise in virtual trade in green water, which we have not quantified in this study. In summary, the blue water (groundwater and

Table 16.2 Long-term regional impacts of restricting groundwater irrigation to renewable resources

Panel A. Percentage change in crop price, production, and area, by region

Region	Crop price (% change)	Crop production (% change)			Cropped area (% change)		
		Total	Irrigated	Rainfed	Total	Irrigated	Rainfed
East Europe	0.23	0.12	−0.71	0.21	0.07	−0.29	0.09
North Africa	1.10	−0.72	−1.21	0.91	0.19	−0.41	0.43
Sub-Saharan Africa	0.13	0.06	−0.46	0.11	0.06	−0.14	0.06
South America	0.29	0.10	−0.50	0.28	0.11	−0.18	0.14
Brazil	0.28	0.12	−1.37	0.33	0.12	−0.77	0.20
Australia and New Zealand	0.34	0.09	−0.90	0.35	0.11	−0.37	0.15
Europe	0.34	0	−1.46	0.35	0.09	−0.62	0.18
South Asia	0.80	−0.40	−1.20	0.74	0.04	−0.54	0.55
Central America	0.38	−0.15	−0.94	0.35	0.09	−0.36	0.24
South Africa	0.63	−1.53	−3.95	0.58	0.11	−1.61	0.32
Southeast Asia	0.24	−0.01	−0.71	0.21	0.06	−0.35	0.16
Canada	0.32	0.36	−0.24	0.37	0.14	−0.13	0.15
United States	0.43	−0.26	−1.45	0.43	0.09	−0.69	0.25
China	0.64	−0.27	−0.91	0.65	0.07	−0.32	0.46
Middle East	1.00	−0.58	−1.19	0.76	0.14	−0.30	0.43
Japan and Korea	0.10	0.01	−0.11	0.11	0.02	−0.08	0.09
Central Asia	0.40	−0.14	−0.36	0.29	0.07	−0.07	0.11
World	0.4	−0.2	−1.1	0.4	0.1	−0.5	0.2

Panel B. Actual change in crop price, production, and area, by region

Region	Change in crop production (1000 MT)			Change in cropped area (1000 ha)		
	Total	Irrigated	Rainfed	Total	Irrigated	Rainfed
East Europe	889	−549	1,390	146	−38	183
North Africa	−2,497	−3,241	738	53	−34	87
Sub-Saharan Africa	783	−568	1,331	130	−13	143
South America	591	−747	1,285	78	−16	95
Brazil	1,108	−1,628	2,709	76	−40	117
Australia and New Zealand	129	−286	400	34	−9	43
Europe	39	−3,303	3,328	96	−80	176
South Asia	−8,820	−15,781	6,576	87	−541	628
Central America	−620	−1,484	869	38	−37	74
South Africa	−1,266	−1,381	276	16	−25	40
Southeast Asia	−80	−2,506	2,381	69	−91	161
Canada	635	−20	617	55	−1	56
United States	−2,983	−6,100	3,189	137	−190	327
China	−12,522	−24,971	11,874	98	−217	315
Middle East	−3,581	−4,992	1,469	81	−67	148
Japan and Korea	11	−87	97	1	−3	4
Central Asia	−193	−326	128	13	−3	16
World	−28,374	−67,968	38,655	1,209	−1,404	2,613

Table 16.3 Trade impacts of restricting groundwater irrigation (percentage change in supply to the domestic market, exports, and imports)

	% Change in supply		% Change in demand
Region	Domestic	Exports	Imports
East Europe	0.02	0.54	−0.45
North Africa	−0.56	−2.83	1.96
Sub-Saharan Africa	0.01	0.78	−0.75
South America	−0.01	0.34	−0.28
Brazil	0.01	0.38	−0.29
Australia and New Zealand	−0.01	0.18	−0.10
Europe	−0.05	0.10	−0.11
South Asia	−0.35	−1.66	1.09
Central America	−0.14	−0.18	−0.02
South Africa	−0.99	−2.29	0.76
Southeast Asia	−0.05	0.40	−0.45
Canada	0.09	0.52	−0.16
United States	−0.16	−0.43	0.12
China	−0.27	−1.07	0.72
Middle East	−0.42	−2.43	1.78
Japan and Korea	−0.01	0.83	−0.82
Central Asia	−0.14	−0.21	−0.02

Table 16.4 Impact of groundwater sustainability policy on virtual blue water exports by source

	%		10^6 m^3	
	Surface water	Groundwater	Surface water	Groundwater
East Europe	1.41	−11.90	59	−152
North Africa	4.87	−48.39	103	−249
Sub-Saharan Africa	1.42	−8.96	25	−74
South America	2.12	−14.26	144	−431
Brazil	2.84	−17.61	152	−551
Australia and New Zealand	1.99	−18.02	52	−170
Europe	2.29	−23.14	238	−928
South Asia	5.26	−26.74	779	−2,984
Central America	3.23	−21.42	239	−647
South Africa	6.30	−28.41	88	−141
Southeast Asia	3.47	−23.54	246	−845
Canada	1.25	−10.30	10	−25
United States	3.62	−27.65	885	−2,935
China	3.54	−21.20	65	−228
Middle East	4.39	−31.38	138	−299
Japan and Korea	0.76	−5.40	2	−6
Central Asia	1.48	−14.71	48	−171
World	3.35	−23.48	3271	−10,835

surface water) virtual trade declines by 10.8 billion m^3 in the wake of this sustainability policy.

4.4 Implications for Employment

The change in employment is calculated assuming a gridded labor market with no explicit modeling of labor mobility across grid cells. Labor is part of the nonland composite input assuming a fixed proportions production process (recall Fig. 16.1). Thus, the demand for labor input follows the changes in demand for the nonland composite input due to changes in intensification. Figure 16.9 illustrates the spatial pattern of change in employment. The pattern is different from that of changes in cropped area and production due to the varying contributions of nonland factors of production by country. The initial numbers for gridded employment were obtained from subregional rates of labor per hectare of cropland. Haqiqi et al. (2022) provide more information on the average number of workers per hectare and per ton of corn-equivalent output in rainfed and irrigated agriculture.

Table 16.5 provides the model results for the aggregated impacts on employment in crop production activities around the world. The findings suggest that employment in irrigated agriculture will decline by about 1.5 million jobs globally. However, employment is expected to increase by 2.5 million jobs in areas with more extensive rainfed agriculture, creating a net gain of one million new jobs globally. Overall, these results suggest an increase of more than half a million jobs in China and South Asia, where domestic cropping area increases with the move to more rainfed production. This is due to the expansion of more extensive rainfed crop production, which requires more labor to work the increased land area. Finally, note that the average worker per hectare of land will be different for the marginal land endogenously added or removed from crop production due to substitutions between the nonland and land–water composites. As the land–water composite becomes scarcer and more costly, an intensification is expected, increasing the average number of workers per hectare of land.

4.5 Sensitivity to Adaptation Margins

Assessing the sensitivity of these findings to key parameter values reveals an interesting finding. The strength of any given individual margin of adaptation is dependent on the other margins. For example, when surface water substitution is limited, there is a stronger price response, and we observe larger adaptation responses from trade and relocation. Alternatively, when substitution in trade is less possible or conversion to rainfed is not feasible, the global irrigated cropped area tends to respond more strongly and there are bigger responses in surface water use. As a consequence, while the component parts of Fig. 16.5 are quite sensitive to

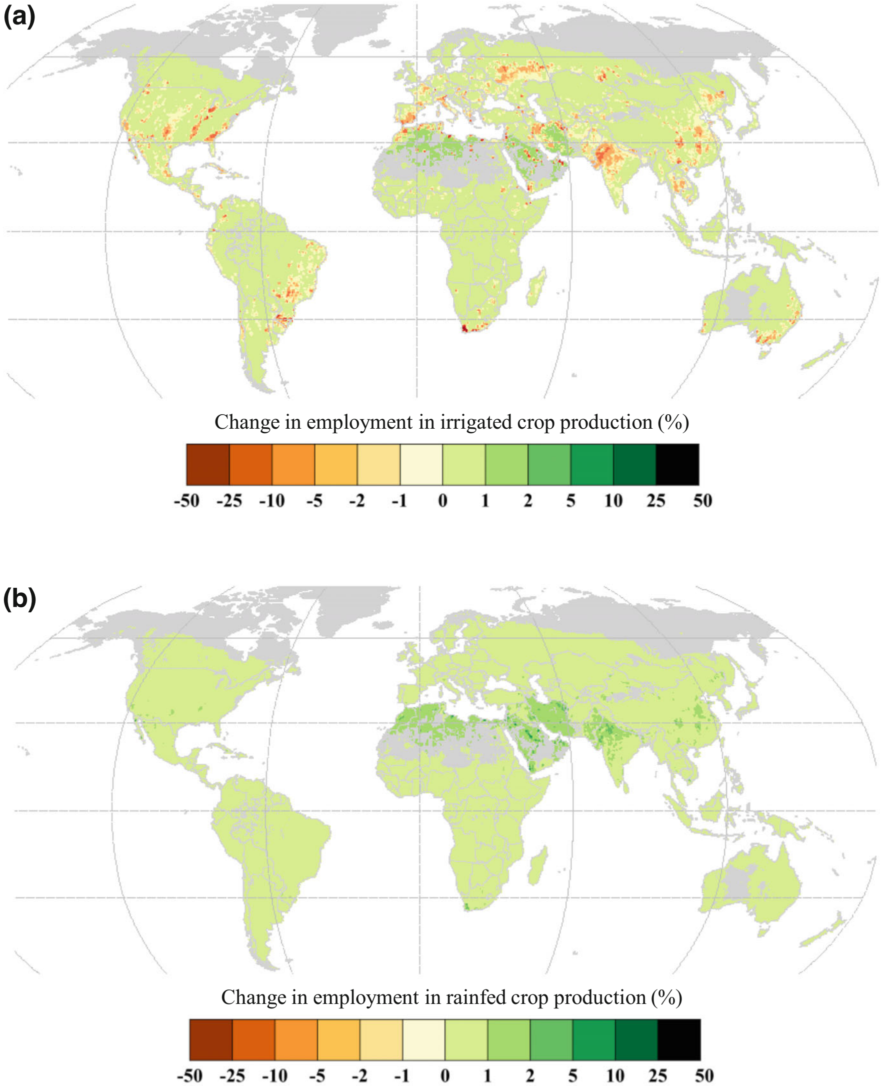

Fig. 16.9 Global changes in agricultural employment in (**a**) irrigated and (**b**) rainfed crop production (%) in response to global groundwater sustainability restrictions *Red* and *yellow* areas indicate a reduction in employment and green indicates increases in employment. While the patterns of change are similar to those of changes in cropped area and production, the reductions in employment are generally smaller, while the increases in employment are larger than the percentage change in cropped area

Table 16.5 Impact of groundwater sustainability policy on employment in crop production by practice and region

	% Change			Change in number of jobs		
	Total	Irrigated	Rainfed	Total	Irrigated	Rainfed
East Europe	0.16	−0.40	0.25	6,107	−1,979	8,086
North Africa	0.28	−0.26	1.03	28,500	−15,631	44,131
Sub-Saharan Africa	0.12	−0.04	0.12	154,544	−1,790	156,336
South America	0.18	−0.15	0.34	7,979	−2,246	10,226
Brazil	0.23	−0.96	0.34	32,697	−11,238	43,935
Australia and New Zealand	0.32	−0.24	0.37	582	−38	620
Europe	0.22	−0.45	0.36	13,417	−4,827	18,244
South Asia	0.11	−0.69	0.83	289,680	−858,248	1,147,920
Central America	0.20	−0.44	0.39	14,867	−7,281	22,148
South Africa	0.31	−1.73	0.55	2,885	−1,654	4,538
Southeast Asia	0.09	−0.40	0.24	83,296	−83,868	167,200
Canada	0.37	0.01	0.38	690	1	690
United States	0.23	−0.83	0.45	4,233	−2,626	6,863
China	0.14	−0.41	0.69	296,608	−425,672	722,272
Middle East	0.52	−0.16	0.88	46,601	−4,980	51,581
Japan and Korea	0.06	−0.01	0.11	662	−52	714
Central Asia	0.17	−0.09	0.36	10,355	−2,271	12,626
World	0.13	−0.52	0.50	993,701	−1,424,400	2,418,129

model parameters, the final impact on global production of eliminating individual margins of adaptation is less than 1%, and the increase in price for more rigid assumptions is also less than 1%. Haqiqi et al. (2022) provide details about these sensitivity analyses and the interactions among the various adaptation margins.

5 Discussion and Conclusion

Stress on groundwater is expected to increase due to income and population growth, and global warming is expected to increase agronomic water requirements. The rising number of drying wells and increasing instances of land subsidence around the world have led to increased attention being given to sustainable groundwater use (Befus et al. 2017; Jasechko and Perrone 2020, 2021; Klasic et al. 2022). However, little is known about the local and global implications of restricting groundwater use to sustainable levels. This study sheds light on the implications of such a scenario on land use and agricultural production.

Recent studies evaluating the impact of restricting groundwater irrigation on agriculture are either geographically limited (United States) or limited in their treatment of global impacts (Baldos et al. 2020; Graham et al. 2021). This study demonstrates that the global impacts of groundwater restrictions on global food availability are largely ameliorated in the long run due to local, regional, and global adaptations. We have also added to this literature by expanding the analysis to include virtual water trade and employment impacts of groundwater governance. The decline in unsustainable groundwater irrigation is accompanied by a decline in virtual trade in blue water, while employment in agriculture increases in the wake of expanding rainfed production. However, even in the long run, local impacts can be very significant for locations with a high dependency on unsustainable groundwater. In some locations, production and employment decline by up to 90%. In locations without alternative sources of employment and food supply, this would have significant local impacts, leading to more than one million jobs lost and likely more than one million families affected. These local impacts will have adverse impacts on the broader economy, a point that our partial equilibrium analysis ignores by holding income constant. Addressing these economy-wide impacts of sustainability policies requires a general equilibrium model, which would typically be implemented at the national level (Calzadilla et al. 2010; Golub and Hertel 2012; Liu et al. 2014).

Our findings suggest that restricting groundwater irrigation could have a significant impact on local irrigated production in hotspots of nonrenewable groundwater irrigation. This directly causes a substantial reduction in agricultural production and employment for these communities. However, the impact of global groundwater sustainability policies is likely to be overestimated if the dynamic responses to restricted groundwater consumption are ignored. We show that these responses at the local and global levels will lessen the negative impact on food prices and production at the regional and global levels. Changes in relative prices at different scales will motivate changes in decisions and market outcomes, including compositional effects at the local level and changes in surface water irrigation, the location of crop production, irrigation extent and intensity, and the international trade in food commodities. Of course, these adjustments are costly and can cause further environmental issues. Overall, our findings suggest that the land-use and deforestation implications of a global groundwater sustainability policy are small and that the long-run impact on food production is less than 1% at the global level. The long-run change in global cropland is also limited to +0.1%, corresponding to +1.2 million hectares of cropland. Expansion as a result of deforestation and cropping of marginal lands could lead to environmental degradation. In addition, as rainfed zones tend to be richer in carbon and biodiversity (Taheripour et al. 2013), other environmental implications of this policy should be studied more carefully, with ecological concerns in mind. This is a critical finding when comparing the likely benefits and costs of such a policy.

Our decomposition framework highlights the possible adaptation mechanisms and demonstrates why ignoring market-mediated responses may lead to the overestimation of the costs of adopting sustainability policies. In addition, the findings are important for understanding the implications of sustainable groundwater use for the virtual trade of blue water. Because of the likely changes in farmers' decisions and economic responses, it is necessary to consider wider market responses when evaluating the impacts of conservation policies. Global environmental and agricultural models that neglect the economic modeling of international trade may overestimate the losses by not accounting for changes in exports and imports based on economic decisions.

Considering the socioeconomic responses in the studies involving impact analyses of sustainability policy will face another key challenge. While sustainability issues are typically very localized and thus require high-resolution land- and water-use models, analyzing the social responses and economic decisions at a fine scale is difficult due to lack of information. Unfortunately, to the best of our knowledge, few global models are capable of high-resolution economic modeling. For example, the GLOBIOM model from the International Institute for Applied Systems Analysis (Valin et al. 2013) is a recursive-dynamic optimization model. However, due to its large size and complexity, the model is not resolved at the level of individual grid cells; rather, it is applied to representative groupings of grid cells, making analysis of local responses to sustainability restrictions more challenging. Similarly, the Global Change Analysis Model (GCAM) provides a framework for modeling groundwater resources and land use, deploying a range of supply- and demand-driven adaptive responses (Turner et al. 2019a, b), but it is implemented at the river-basin level. However, high-resolution analysis is important due to the heterogeneity of land and water use among grid cells within aquifers (e.g., the sustainability restrictions and responses would be different between the Northern Plains and southern regions of the Ogallala Aquifer in the United States). Here, SIMPLE-G introduces one of the first frameworks capable of modeling land use and water use decisions at the grid-cell level while also considering grid-cell-specific responses within local, regional, and global markets. This was possible thanks to close collaboration with hydrologists in the Water Systems Analysis Group of the University of New Hampshire. Further research is required to improve the ability of global models to integrate economic and environmental sciences considering cross-system feedback.

The reliance on virtual water trade carries the risk that many countries will not intervene to restore groundwater stability but rather will avoid the political and administrative challenges of regulation, safe in the knowledge (or more likely, hope) that virtual water will continue to compensate for reduced local production. This route will eventually generate far more severe local (and global) consequences. Intervening to restore stability, which we have endeavored to model in this study, reduces the *average* water available from groundwater but crucially preserves the flexibility and emergency buffer resources that renewable groundwater provides. If mining continues, that function will disappear because aquifers will effectively run dry, salinizing or becoming so deep that recharge no longer reaches the saturated zone in a useful timeframe or the cost of abstraction becomes prohibitive. The reduction in water availability implied in that scenario—a loss of both volume and flexibility—will have far more profound consequences locally and globally. The implication of this is that while introducing governance "now" is relatively cheap, failure to do so will be very expensive.

With increasing risks of megadroughts in the future, groundwater resources play an important role by acting as a buffer in times of extreme drought when there is no surface water available. They provide a temporary source for essential needs (including drinking water). By incurring modest production losses today, nations can reserve their groundwater resources for a future time when they will be more valuable. This intertemporal substitution is an important topic for future exploration.

In closing, this study has provided insights into the long-run costs and benefits of groundwater sustainability policy. However, we did not model the transition costs and long-run benefits of sustainable groundwater use. During the transition period—and while farmers adjust their decisions based on market outcomes—there can be a high reduction in local production, employment, and farm income. We find that aggregate employment will increase in the long run, ensuring that communities that use water sustainably will avoid the risk of running out of groundwater when it is most needed. However, there are still uncertainties about the actual ramifications of ambitious global sustainability policies. How big are the unintended consequences that might occur from local water conservation, potentially spurring deforestation and excess fertilizer use in distant corners of the world? Can rigidities within the labor market reduce the effectiveness of even the most well-intentioned policy efforts? These questions call for future research to shed light on the different benefits and costs of sustainability policies and on the synergies and trade-offs between sustainability goals within planetary boundaries.

Acknowledgments and Competing Interests This work was supported by the National Science Foundation CBET-1855937, CBET-1805808, OISE-2020635, and DEB-1924111 and the US Department of Agriculture, National Institute of Food and Agriculture, grant #2019–67,023-29,679.

The findings and conclusions presented in this chapter are those of the authors and should not be construed to represent any official determination or policy of the US Department of Agriculture (USDA), the US government, the Department of Energy (DOE), or the National Science Foundation (NSF). Furthermore, we declare that there is no conflict of interest related to this work.

References

Allan, Tony. 1997. "Virtual water": A long term solution for water short Middle Eastern economies? In *Festival of science*. Leeds: British Association for the Advancement of Science.

Allan, John Anthony. 2003. Virtual water – The water, food, and trade nexus. Useful concept or misleading metaphor? *Water International* 28: 106–113. https://doi.org/10.1080/02508060.2003.9724812.

Allan, Tony. 2011. *Virtual water: Tackling the threat to our planet's most precious resource*. London: Bloomsbury Publishing.

Baldos, C. Uris Lantz, Iman Haqiqi, Thomas W. Hertel, Mark Horridge, and J. Liu. 2020. SIMPLE-G: A multiscale framework for integration of economic and biophysical determinants of sustainability. *Environmental Modelling & Software* 133: 104805. https://doi.org/10.1016/j.envsoft.2020.104805.

Befus, Kevin M., Scott Jasechko, Elco Luijendijk, Tom Gleeson, and M. Bayani Cardenas. 2017. The rapid yet uneven turnover of Earth's groundwater. *Geophysical Research Letters* 44: 5511–5520. https://doi.org/10.1002/2017GL073322.

Bierkens, Marc F.P., and Yoshihide Wada. 2019. Non-renewable groundwater use and groundwater depletion: A review. *Environmental Research Letters* 14: 063002. https://doi.org/10.1088/1748-9326/ab1a5f.

Bredehoeft, John D. 2002. The water budget myth revisited: Why hydrogeologists model. *Groundwater* 40: 340–345. https://doi.org/10.1111/j.1745-6584.2002.tb02511.x.

Calzadilla, Alvaro, Katrin Rehdanz, and Richard S.J. Tol. 2010. The economic impact of more sustainable water use in agriculture: A computable general equilibrium analysis. *Journal of Hydrology* 384: 292–305. https://doi.org/10.1016/j.jhydrol.2009.12.012.

Chapagain, A.K., and A.Y. Hoekstra. 2011. The blue, green and grey water footprint of rice from production and consumption perspectives. *Ecological Economics* 70: 749–758. https://doi.org/10.1016/j.ecolecon.2010.11.012.

Chatterjee, Rana, and Ranjan Kumar Ray. 2016. A proposed new approach for groundwater resources assessment in India. *Journal of the Geological Society of India* 88: 357–365. https://doi.org/10.1007/s12594-016-0498-2.

Chinnasamy, Pennan, and Govindasamy Agoramoorthy. 2016. India's groundwater storage trends influenced by tube well intensification. *Ground Water* 54: 727–732. https://doi.org/10.1111/gwat.12409.

Dalin, Carole, Yoshihide Wada, Thomas Kastner, and Michael J. Puma. 2017. Groundwater depletion embedded in international food trade. *Nature* 543: 700–704. https://doi.org/10.1038/nature21403.

Dee, D.P., S.M. Uppala, A.J. Simmons, P. Berrisford, P. Poli, S. Kobayashi, U. Andrae, et al. 2011. The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society* 137: 553–597. https://doi.org/10.1002/qj.828.

Dizard, John. 2022. Ukraine war disrupts global market for grains. *Financial Times*, February 26.

Famiglietti, J.S. 2014. The global groundwater crisis. *Nature Climate Change* 4: 945–948. https://doi.org/10.1038/nclimate2425.

Galloway, Devin L., and Thomas J. Burbey. 2011. Review: Regional land subsidence accompanying groundwater extraction. *Hydrogeology Journal* 19: 1459–1486. https://doi.org/10.1007/s10040-011-0775-5.

Gleeson, Tom, Yoshihide Wada, Marc F.P. Bierkens, and Ludovicus P.H. Van Beek. 2012. Water balance of global aquifers revealed by groundwater footprint. *Nature* 488: 197–200. https://doi.org/10.1038/nature11295.

Golub, Alla A., and Thomas W. Hertel. 2012. Modeling land-use change impacts of biofuels in the GTAP-BIO framework. *Climate Change Economics* 3: 1250015. https://doi.org/10.1142/S2010007812500157.

Graham, Neal T., Gokul Iyer, Mohamad I. Hejazi, Son H. Kim, Pralit Patel, and Matthew Binsted. 2021. Agricultural impacts of sustainable water use in the United States. *Scientific Reports* 11: 17917. https://doi.org/10.1038/s41598-021-96243-5.

Grogan, Danielle. 2016. *Global and regional assessments of unsustainable groundwater use in irrigated agriculture*. Dissertation, Durham, NH: University of New Hampshire. https://www.proquest.com/dissertations-theses/global-regional-assessmentsunsustainable/docview/1802824016/se-2.

Grogan, Danielle S., Dominik Wisser, Alex Prusevich, Richard B. Lammers, and Steve Frolking. 2017a. The use and re-use of unsustainable groundwater for irrigation: A global budget. *Environmental Research Letters* 12: 034017. https://doi.org/10.1088/1748-9326/aa5fb2.

———. 2017b. The use and re-use of unsustainable groundwater for irrigation: A global budget. *Environmental Research Letters* 12: 034017. https://doi.org/10.1088/1748-9326/aa5fb2.

Grogan, Danielle S., Shan Zuidema, and Stanley Glidden. 2022. *Water balance model (WBM) open source release version 1.0.0 ancillary data (version 1.0.0)*. University of New Hampshire Earth Systems Research Center. https://doi.org/10.34051/d/2022.2.

Haqiqi, Iman, Chris J. Perry, and Thomas W. Hertel. 2022. When the virtual water runs out: Local and global responses to addressing unsustainable groundwater consumption. *Water International* 47: 1060–1084. https://doi.org/10.1080/02508060.2023.2131272.

Haqiqi, Iman, Danielle S. Grogan, Marziyeh Bahalou Horeh, Jing Liu, Uris L.C. Baldos, Richard Lammers, and Thomas W. Hertel. 2023. Local, regional, and global adaptations to a compound pandemic-weather stress event. *Environmental Research Letters* 18: 035005. https://doi.org/10.1088/1748-9326/acbbe3.

Jasechko, Scott, and Debra Perrone. 2020. California's Central Valley groundwater wells run dry during recent DROUGHT. *Earth's Futures* 8: e2019EF001339. https://doi.org/10.1029/2019EF001339.

———. 2021. Global groundwater wells at risk of running dry. *Science* 372: 418–421. https://doi.org/10.1126/science.abc2755.

Klasic, Meghan, Amanda Fencl, Julia A. Ekstrom, and Amanda Ford. 2022. Adapting to extreme events: Small drinking water system manager perspectives on the 2012–2016 California Drought. *Climatic Change* 170: 26. https://doi.org/10.1007/s10584-021-03305-8.

Liu, Jing, Thomas W. Hertel, Farzad Taheripour, Tingju Zhu, and Claudia Ringler. 2014. International trade buffers the impact of future irrigation shortfalls. *Global Environmental Change* 29: 22–31. https://doi.org/10.1016/j.gloenvcha.2014.07.010.

Liu, Jing, Thomas W. Hertel, Richard B. Lammers, Alexander Prusevich, Uris Lantz C. Baldos, Danielle S. Grogan, and Steve Frolking. 2017. Achieving sustainable irrigation water withdrawals: Global impacts on food security and land use. *Environmental Research Letters* 12: 104009. https://doi.org/10.1088/1748-9326/aa88db.

Martens, Brecht, Diego G. Miralles, Hans Lievens, Robin van der Schalie, Richard A.M. de Jeu, Diego Fernández-Prieto, Hylke E. Beck, Wouter A. Dorigo, and Niko E.C. Verhoest. 2017. GLEAM v3: Satellite-based land evaporation and root-zone soil moisture. *Geoscientific Model Development* 10: 1903–1925. https://doi.org/10.5194/gmd-10-1903-2017.

Mekonnen, Mesfin M., and Arjen Y. Hoekstra. 2020. Sustainability of the blue water footprint of crops. *Advances in Water Resources* 143: 103679. https://doi.org/10.1016/j.advwatres.2020.103679.

Rienecker, Michele M., Max J. Suarez, Ronald Gelaro, Ricardo Todling, Julio Bacmeister, Emily Liu, Michael G. Bosilovich, et al. 2011. MERRA: NASA's modern-era retrospective analysis for research and applications. *Journal of Climate* 24: 3624–3648. https://doi.org/10.1175/JCLI-D-11-00015.1.

Rosa, Lorenzo, Davide Danilo Chiarelli, Tu Chengyi, Maria Cristina Rulli, and Paolo D'Odorico. 2019. Global unsustainable virtual water flows in agricultural trade. *Environmental Research Letters* 14: 114001. https://doi.org/10.1088/1748-9326/ab4bfc.

Saha, Suranjana, Shrinivas Moorthi, Wu Xingren, Jiande Wang, Sudhir Nadiga, Patrick Tripp, David Behringer, et al. 2014. The NCEP climate forecast system version 2. *Journal of Climate* 27: 2185–2208. https://doi.org/10.1175/JCLI-D-12-00823.1.

Siebert, Stefan, and Petra Döll. 2008. *The Global Crop Water Model (GCWM): Documentation and first results for irrigation crops*, Frankfurt hydrology paper 7. Frankfurt: Goethe University.

———. 2010. Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. *Journal of Hydrology* 384: 198–217. https://doi.org/10.1016/j.jhydrol.2009.07.031.

Taheripour, Farzad, Thomas W. Hertel, and Jing Liu. 2013. The role of irrigation in determining the global land use impacts of biofuels. *Energy, Sustainability and Society* 3: 4. https://doi.org/10.1186/2192-0567-3-4.

Turner, Sean W.D., Mohamad Hejazi, Katherine Calvin, Page Kyle, and Sonny Kim. 2019a. A pathway of global food supply adaptation in a world with increasingly constrained groundwater. *Science of the Total Environment* 673: 165–176. https://doi.org/10.1016/j.scitotenv.2019.04.070.

Turner, Sean W.D., Mohamad Hejazi, Catherine Yonkofski, Son H. Kim, and Page Kyle. 2019b. Influence of groundwater extraction costs and resource depletion limits on simulated global nonrenewable water withdrawals over the twenty-first century. *Earth's Future* 7: 123–135. https://doi.org/10.1029/2018EF001105.

Valin, Hugo, Petr Havlík, Niklas Forsell, Stefan Frank, Aline Mosnier, Daan Peters, Carlo Hamelinck, Matthias Spöttle, and Maarten van den Berg. 2013. Description of the GLOBIOM (IIASA) model and comparison with the MIRAGE-BioF (IFPRI) model. *Crops* 8: 10.

Wada, Yoshihide, L.P.H. Van Beek, and Marc F.P. Bierkens. 2012. Nonsustainable groundwater sustaining irrigation: A global assessment. *Water Resources Research* 48: 2011WR010562. https://doi.org/10.1029/2011WR010562.

Wada, Y., D. Wisser, and M.F.P. Bierkens. 2014. Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources. *Earth System Dynamics* 5: 15–40. https://doi.org/10.5194/esd-5-15-2014.

Willmott, Cort J., and Kenji Matsuura. 2001. *Terrestrial air temperature and precipitation: Monthly and annual time series (1950–1999) (version 1.02)*. Newark: University of Delaware Center for Climatic Research.

Wisser, D., B.M. Fekete, C.J. Vorosmarty, and A.H. Schumann. 2010. Reconstructing 20th century global hydrography: A contribution to the Global Terrestrial Network- Hydrology (GTN-H). *Hydrolology and Earth System Science* 14: 1–24. https://doi.org/10.5194/hess-14-1-2010.

Woo, Jungha, Lan Zhao, Danielle S. Grogan, Iman Haqiqi, Richard Lammers, and Carol X. Song. 2022. C3F: Collaborative container-based model coupling framework. In *PEARC '22: Practice and experience in advanced research computing*. Boston: Association for Computing Machinery. https://doi.org/10.1145/3491418.3530298.