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When the virtual water runs out: local and global responses to addressing unsustainable groundwater consumption

Iman Haqiqi [a], Chris J. Perry [b] and Thomas W. Hertel [a]

[a]Department of Agricultural Economics, Purdue University, West Lafayette, IN, USA; [b]Independent Researcher, London, UK

ABSTRACT

Given the growing importance of groundwater in irrigated crop production, policies aimed at restricting groundwater use create fears of intensified food insecurity. Yet, a comprehensive quantitative analysis is required to evaluate the impacts of groundwater sustainability restrictions on food system. Using a multi-scale multi-system framework integrating economic and biophysical determinants of sustainability, we find that the local economic impacts of a groundwater sustainability policy are often substantial. However, due to market-mediated responses, including surface water substitution, expansion of rainfed production, relocation and virtual trade in blue water, the final impact on global food prices and production is surprisingly modest.

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Virtual water; sustainability; food security; adaptation; land use

Introduction

Tony 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.

Allan's main interest was in the consequence of these transfers: the extent to which political stability was preserved in countries that rely on imported 'virtual water' to ensure food security. There are two dimensions to this linkage. First, the avoidance of 'water wars' as the import of virtual water made it unnecessary to 'capture' the underlying natural resource itself; and second, as a direct consequence of this trade, enhanced food security. Few rulers of fragile democracies – and non-democracies – could survive long when the shops have no bread (Dizard, 2022).

In this paper, we explore another perspective on virtual water: many surplus food-producing countries are 'exporting' large quantities of groundwater that is being 'mined' from their aquifers. Stated bluntly, they are exporting their environment, free of charge, to food-importing countries. There will be consequences to this simple insight, and we explore, within a multi-scale framework, through a set of models and calculations, the impacts of a 'best case' scenario whereby groundwater consumption is constrained to

CONTACT Iman Haqiqi ihaqiqi@purdue.edu
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a 'sustainable' equilibrium by prudent management. What changes are likely in the pattern of commodity production, locally and globally, and what changes in prices can be expected as a consequence of such 'good governance'?

Sustainable groundwater use – some definitions

For groundwater, what does sustainability mean? Groundwater systems are often highly complex, comprising different layers that are sometimes directly linked, sometimes partially linked and sometimes completely independent, 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 – though 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) and useful analysis of the status of a groundwater system, and the consequences of over-abstraction, require 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 towards streams or surrounding aquifers, and pumping. When these two sets of flows are equal, the water table remains, when observed over a period of years, essentially constant, varying seasonally and annually due to actual rainfall patterns, associated pumping rates, etc. Yet even from this simple formulation we see immediately that any increase in net abstraction from an aquifer – for example, by introducing a new tubewell – 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 outflow(s) is reduced – lateral outflows to streams, or 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 re-established.

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, and again, over a period of years, the observed status of the groundwater system will remain constant. Yet the impacts of the reduced outflows to vegetation and local streams may cause damage to a downstream wetland or aspects of the natural landscape which 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 – irrigators, fishermen, ferry operators, etc. – will similarly have 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, in each of which the stability test (inflows = outflows) is met (e.g., Chinnasamy & 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, or salinized, or otherwise rendered unfit for use. During this stage, there are no points of equilibrium. The water table continues to fall until eventually the final equilibrium arrives when an aquifer is depleted to the point that 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 (e.g., Chatterjee & Ray, 2016) This position is apparently based on the assumption that the 'available' resource is currently disappearing somewhere, because 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 (measurements, observations, modelling) contribute to political decisions that determine allocations. Here we include in the spectrum of political interventions the decision to do nothing and allow the tragedy of the commons (Hardin) to unfold. While to our knowledge, this policy is never made explicit, this scenario is not rare.

In fact, all water resources development (e.g., diversion from rivers, construction of dams, water harvesting, de- or re-forestation, conversion to new irrigation technologies) involves some degree of reallocation of water among users and uses. Food security, and rural employment are increased 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, and it is the role of governments, through political processes, to evaluate the underlying trade-offs and intervene appropriately.

In sum, there are four stages of groundwater development: (1) the natural state of precipitation, vegetation and runoff; (2) progressive human interventions that expand use (agriculture, domestic water supply, etc.) 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 & Burbey, 2011); (b) compaction of the soil, so 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 (b), above, and the ever-increasing depth to the water table. Unfortunately, many aquifers around the world are at the third stage listed above, and in the absence of interventions by the relevant authorities, they will automatically progress to the fourth stage of irreparable damage.

In this paper, we assess the impacts of restricting groundwater abstraction to sustainable levels – halting 'mining' of groundwater, and returning to stage 2, above. 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 the 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 preserving a resource that can be assigned to priority uses during periods of severe drought. The alternative of allowing aquifer depletion and loss of the buffer function will undoubtedly be far more costly – an issue to be addressed in a further study.

The state of the world's groundwater

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

Added to these concerns, the rate of increase is remarkable. According to Wada et al. (2014) global aquifer depletion almost tripled between 1960 and 2010, and is projected to almost double again by 2099 (though 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.

The next sections address the likely impacts – locally and globally – of the reductions in water supply that would bring stability to aquifers. As background, the expectations of Wada et al. and of Famiglietti are quoted in full:

> The current degree of non-sustainable use may compromise the future livelihoods of millions of people and their living standards.(Wada et al., 2014)

> 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.(Famiglietti, 2014)

Methods

Experiment design

To permit a unified analysis of groundwater sustainability policies, we pair a hydrological model with an agro-economic model of global crop production at the level of 5--arc minute grid cells (Figure 1). These two models have been successfully linked (Woo et al., 2022) and have shed light on the impacts of surface water scarcity (Liu et al., 2017),

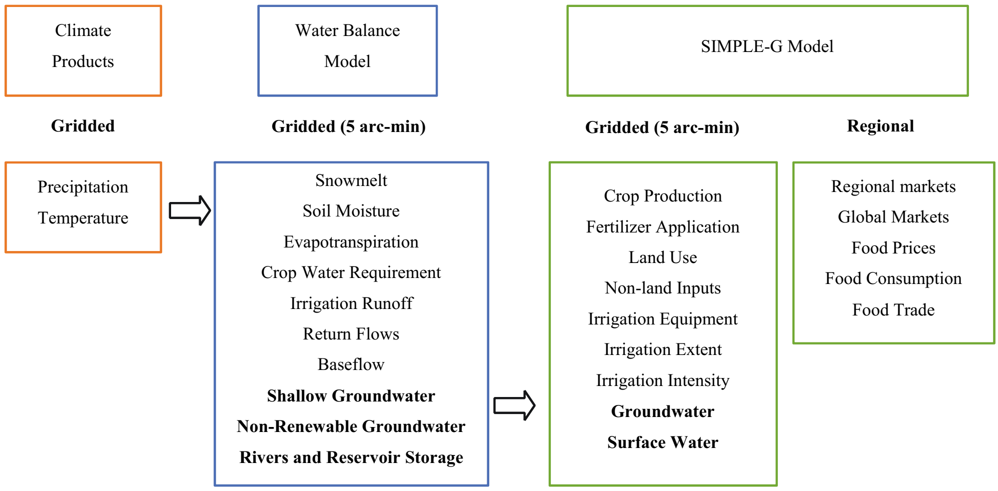

Figure 1. Employing hydroclimatic information to inform the economic model about irrigation water availability and non-renewable groundwater irrigation. The Water Balance Model (WBM) is a global gridded framework for modelling water mass balance at each grid cell. It simulates the vertical water exchange between atmosphere and land as well as the horizontal flow of water through river networks, baseflow and run-offs. Daily precipitation and temperature from climate products as well as information regarding agriculture and water demand at each location are the input to WBM. The simulated changes in surface water and groundwater volumes are fed into the SIMPLE-G model where decisions about land and water use are modelled. The regional outcomes are determined via the interaction of gridded crop outputs and regional as well as global market responses.

as well as the yield impacts of compound hydro-climatic extremes (Haqiqi et al., 2021). Here, we employ the outputs of the Water Balance Model (WBM) following Grogan et al. (2017). WBM is a validated and widely used macro-scale hydrological model (Wisser et al., 2010; Grogan, 2016; Grogan et al., 2022). Consumptive water requirements are calculated by crop and by growth stage, based on soil moisture, temperature and irrigation status. The sources of irrigation in WBM can be reservoirs, rivers, shallow groundwater and non-renewable groundwater if available. The model also considers non-beneficial consumption and return flows through irrigation runoff, baseflow between groundwater and surface water, and percolation of irrigation return flows to shallow groundwater. The multi-scale nature of this model, building from the grid cell to global hydrology, makes it an appropriate model for this study.

To assess the sustainable level of groundwater abstraction, we follow Grogan (2016, 2017), wherein the maximum allowed level of groundwater use is determined such that there is zero non-renewable 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 WBM over the period 1980–2009, while not allowing abstraction from non-renewable 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 use 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 & 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 later.

One challenge we face is that SIMPLE-G-Global is constructed based on economic and agricultural information *c*.2017. In other words, the crop production, cropped area, yields and prices reflect a more recent market condition than that reflected in the historical weather data. In addition, the size of SIMPLE-G grid-cells is 5 arc-min, while the historic WBM runs are for global 30 arc-min grid cells. Having determined the long-run historic sustainable level of groundwater withdrawals, 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) at 5 arc-min grid cells. This allows for consistency with the 2017-based economic model. We assume all the smaller (5 arc-min) grid cells follow their underlying larger grid-cells in terms of non-renewable groundwater rates.

Table 1 summarizes the situation for major groundwater users in the world. Overall, 27% of irrigation water consumption is linked to non-renewable resources. However, this is substantially higher in some regions: 62% for Iran and 39% for India. Compared with total global crop water demand, the non-renewable groundwater contribution is around 6% (although this 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 other studies in the literature (Bierkens & Wada, 2019; Chapagain & Ysbert Hoekstra, 2011; Mekonnen & Hoekstra, 2020; Siebert & Döll, 2010; Gleeson et al., 2012).

Figure 2 shows the distribution of cropped area relying on irrigation and non-renewable groundwater around 2017. ‘Green’ water is that provided to crops by rainfall; ‘blue’ water comprises irrigation water from surface and groundwater. Figure 2 shows the hotspots of groundwater crisis are most prominent in the United States, China, India, Pakistan and the Middle East where crop water demand in some of the grid cells is obtained nearly entirely from non-renewable resources. As seen here, the problem of non-renewable groundwater abstraction tends to be quite concentrated.

Table 1. Total crop water demand and contribution of non-renewable resources for major groundwater users, *c*.2017.

	Total crop water demand	Green water contribution		Blue water contribution		Non-renewable groundwater	
	($km^3\ yr^{-1}$)	($km^3\ yr^{-1}$)	%	($km^3\ yr^{-1}$)	%	($km^3\ yr^{-1}$)	%
India	493	203	41%	289	59%	112	23%
China	438	223	51%	215	49%	64	15%
Pakistan	101	2	2%	98	98%	21	21%
USA	428	374	87%	55	13%	13	3%
Iran	6	2	31%	4	69%	3	43%
Mexico	48	36	76%	12	24%	3	5%
World	3848	2934	76%	915	24%	244	6%

Note: The percentage shows the share in total crop water consumption.
Source: Outputs of global Water Balance Model (WBM) based on GLEAM v3. Aggregated from 5 arc-min grid cells (authors’ calculations based on Grogan, 2016, 2017, 2022).

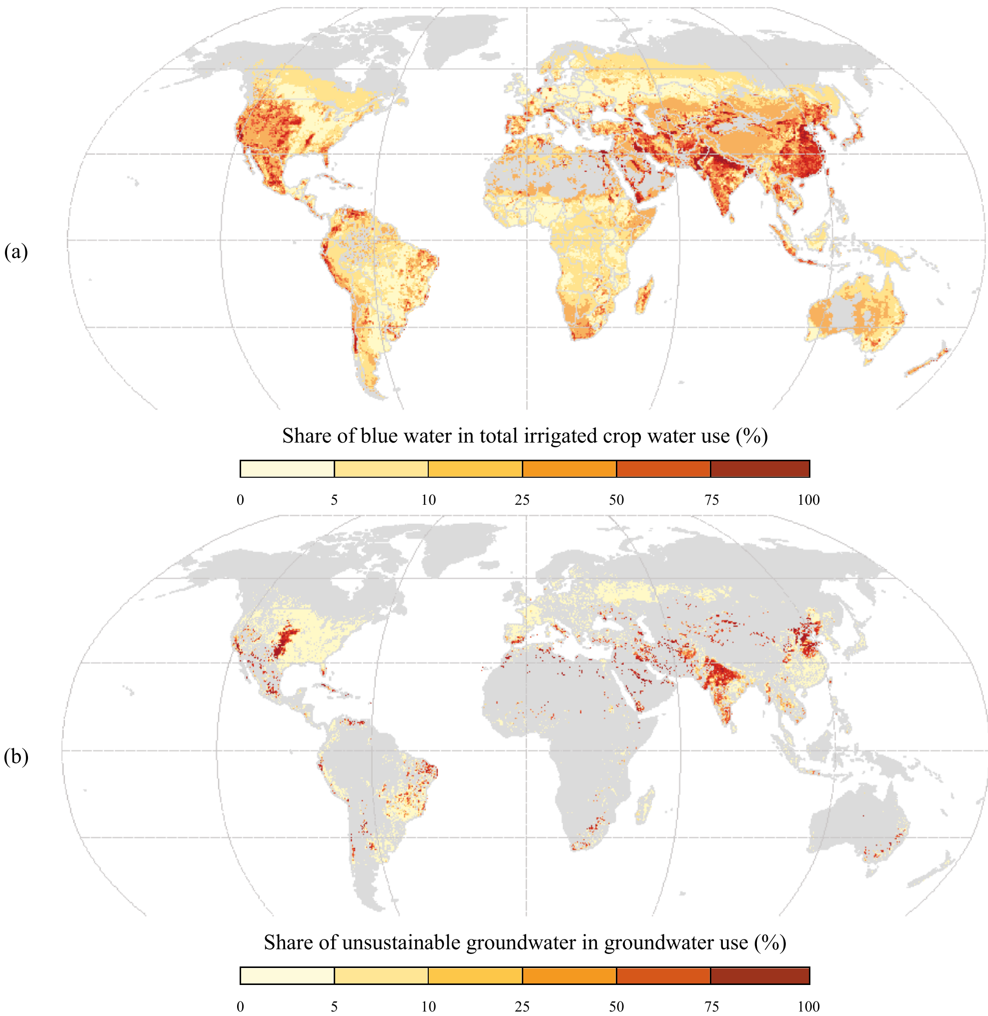

Figure 2. Spatial distribution and the significance of irrigation and unsustainable groundwater. (a) Share of blue water in total gridded crop water consumption around 2017. Red colouring means there is little green water available to crops. Therefore, if there is crop production in these locations, it must be irrigated. (b) Share of unsustainable groundwater in total gridded irrigation water consumption around 2017. Colour red means crop production mainly relies on unsustainable groundwater. Grey colouring refers to areas not irrigated.

To capture the local, national, and global impact and responses to sustainability groundwater restrictions, we employ a gridded economic model called SIMPLE-G (Haqiqi et al., 2020) with more than 1.3 million grid cells (5 arc-min, squares of width 9.26 km at the equator). Major components of regional food demand and gridded crop supply of the SIMPLE-G model are illustrated in Figure 3. Each grid cell represents a distinct unit of agricultural production on which competition for land and water resources play out, within and between rainfed and irrigated crop production. SIMPLE-G is a multiscale framework for the integration of economic and biophysical determinants of sustainability. It includes markets at regional, subregional and grid-cell

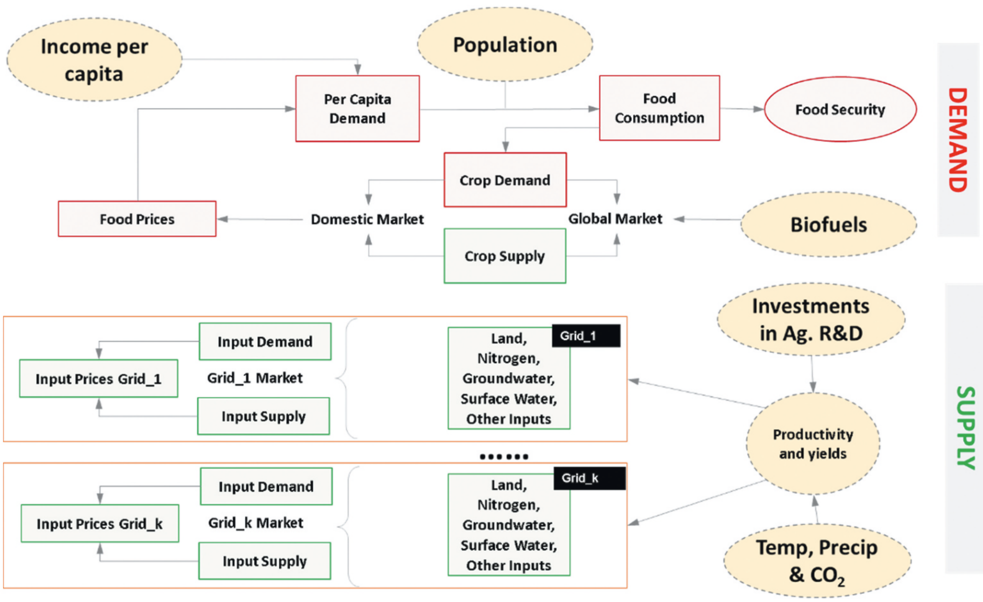

Figure 3. Overall structure of the SIMPLE-G model. The model determines the global and local prices of agricultural commodities in a supply–demand framework. The demand for agricultural products by global regions is considered as a function of population, per capita income, biofuel mandates and global prices. The demand endogenously determines the likely shifts in diets and the ensuing implications for food security. The supply side is modelled at the grid-cell level as a function of market prices, technological change and weather, although the latter two forces are unchanging in this study. The model determines the equilibrium local prices, land use, water use, fertilizer application and agricultural demand for other inputs.

levels. In the face of groundwater sustainability restrictions, the model solves for the gridded equilibrium level of irrigated and non-irrigated land, extraction of groundwater and surface water for irrigation and crop production. It also determines the new equilibrium local, national and global crop prices, along with domestic use and international trade in crops. Crops are consumed directly, as well as indirectly in the form of processed food, as well as livestock products, at the level of 17 world regions, with these consumer demands for foodstuffs responding to prices and per capita incomes.

To focus our analysis on the impact of groundwater sustainability restrictions, we assume no changes in regional population, income and biofuel demands. However, the demand responses to changes in food prices will be captured in the interaction of demand and supply at the regional markets. Also, we assume no change in local climate conditions to allow us to clearly assess the impact of groundwater restrictions alone. For a study considering compound socio-economic and environmental stressors within this framework, see Haqiqi et al. (2020).

The SIMPLE-G model does not model the behaviour of individual farmers, but the outcome at the aggregate level at each grid cell for all crops aggregated into a single composite commodity. The crop output of each grid cell is differentiated from other grid cells, reflecting these differences in crop composition. This product differentiation applies at both national and regional (17 world regions) levels. In any given grid cell,

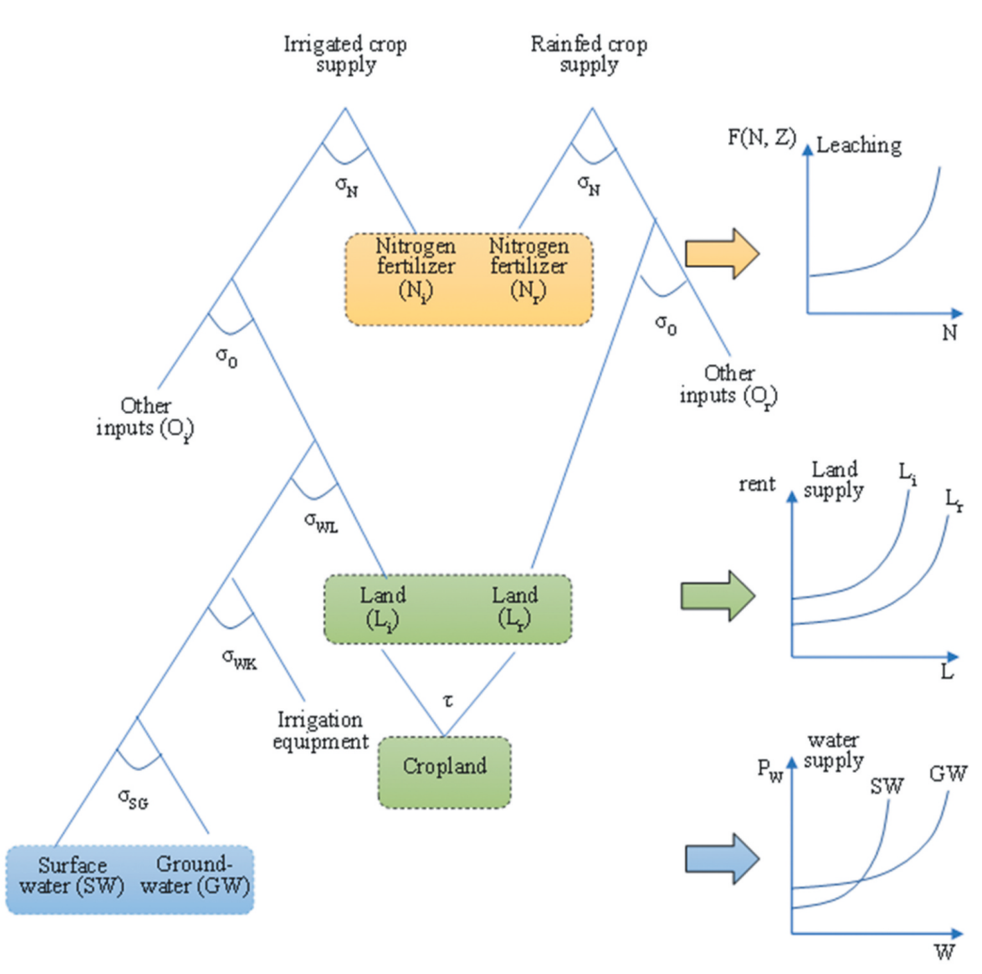

Figure 4. Schematic representation of grid-specific functional forms. SIMPLE-G assumes a supply–demand framework for production inputs at each grid-cell. (a) To calculate the demand for inputs, a nested constant elasticity of substitution (CES) function for irrigated and rainfed practices is used. This is a common function widely used in economics due to its flexibility in handling highly non-linear relationships working based on relative prices and production scale. Here σ shows the substitution parameter for each nest. The bottom nest (SG) determines the surface water (SW) and groundwater (GW) composite. Then the water-capital (WK) nest determines the combination of water and irrigation equipment. The water-land (WL) nest then determines water and land composite. Finally, the N and O nests determine how production combines WL with fertilizer and other inputs. (b) To calculate the supply of land, a constant elasticity of transformation is assumed with quantity-preserving characteristics. (c) To determine the supply schedule of groundwater and surface water, the supply elasticities are determined based on the volume of available water (Haqiqi, 2019).

yield, water use and nitrogen fertilizer use in crop production are weighted averages over all crops, but we distinguish between two farming practices within each grid cell: rainfed versus irrigated crop production. Figure 4 illustrates the gridded supply structure and agricultural production function with major inputs and parameters of the model for both irrigated and rainfed crop supply.

Virtual water trade is introduced in this version of SIMPLE-G to represent the water embedded in international trade of agricultural commodities. There is a rich literature around the concept, applications and modelling 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 (for details, see the supplemental data online).

Implementation of groundwater restrictions in the SIMPLE-G model

As discussed above, the groundwater sustainability limits are calculated by the Water Balance Model (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 and 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 the spillover effects. Therefore, we consider additional scenarios whereby the system responds to these direct impacts. A 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 consider changes in irrigation intensity in terms of water suppled 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 modelled. All these changes can affect the rate of recharge to groundwater and thus changes the initial sustainability limit. They 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 the decisions regarding surface water, irrigation intensity, and irrigation extent are transferred to the WBM. Then WBM will give us the 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.

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 consequences of this 'first round' of responses to the groundwater sustainability restriction is a 12.3% reduction in global crop production (around 2 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 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 and other inputs, 'rainfed conversion', 'relocation' and 'global trade'. The initial margin of adjustment involves substituting surface water for groundwater, where feasible, and using other farm inputs more intensively (Figure 5, 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 (3.18% increase in Figure 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 Figure 5 (bar d) is due to the national relocation of production. Rising prices in countries where groundwater is restricted motivates expansion of national 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 Figure 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'. Figure 5 (bar e) offsets 3.32% of the global production decline. Table 5, columns 2 and 4, provides more detail on the change in virtual water trade due to the groundwater sustainability policy.

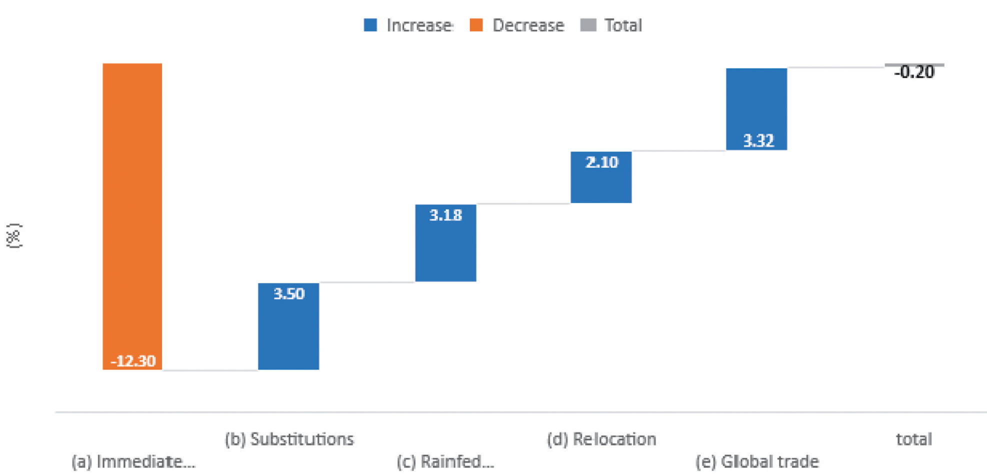

Figure 5. Decomposition of global crop response to global groundwater sustainability restrictions. The leftmost (orange) bar shows the immediate/direct impact before adaptation. The subsequent bars incorporate successive market-mediated adaptations; (b) substitution of surface for groundwater as well 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.

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 and groundwater). Due to multi-scale 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 an increase in global surface water withdrawal by 3.42% in the long run. On the other hand, despite the fact that irrigated production has declined by 1.03%, rainfed production has increased by 0.4%. This nearly offsets the reduction in irrigated output. This is also reflected in cropped area: −0.43% change in irrigated area and +0.21% change in the rainfed area, leading to a global cropped area increase of 0.21% (Table 4, columns 2–8).

At the country level, the long-run production impacts are small as similar adaptations can occur within a country. The findings suggest that in China, India, the United States, Pakistan and Iran, total annual production will decline by −12.5, −6.0, −3.0, −2.6 and −2.1 million tons of corn equivalent crops. Also, the overall long-run employment impacts are positive for many countries. According to the model output, in China, India, Indonesia, Bangladesh and Turkey there will be 296,600, 236,900, 66,700, 57,500 and 34,600 new agricultural jobs due to spillovers and expansions in croplands. The largest negative employment effects are in Pakistan and Vietnam by −36,000 and −24,800 jobs.

Spatial distribution of the impacts

This section illustrates the final changes in equilibrium levels of input demand and crop supply in response to enforcement of sustainable groundwater use, globally. These are equilibrium outcomes of the model and reflect interactions between local and global agricultural markets. The spatial heterogeneity of the impacts is due both to heterogeneity in the magnitude of the reduction in groundwater as well as 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.

Impact on cropped area

Figure 6 shows the spatial distribution of the impact on cropped area. The red and yellow colourings illustrate contraction and green colouring shows expansion in 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 is a decline in cropped area. These hotspots include California's Central Valley, the US Ogallala Aquifer, the Mississippi basin, parts of India and Pakistan, and parts of China, North Africa and the Middle East. The analysis projects a slight increase in both irrigated and non-irrigated area for the rest of the world.

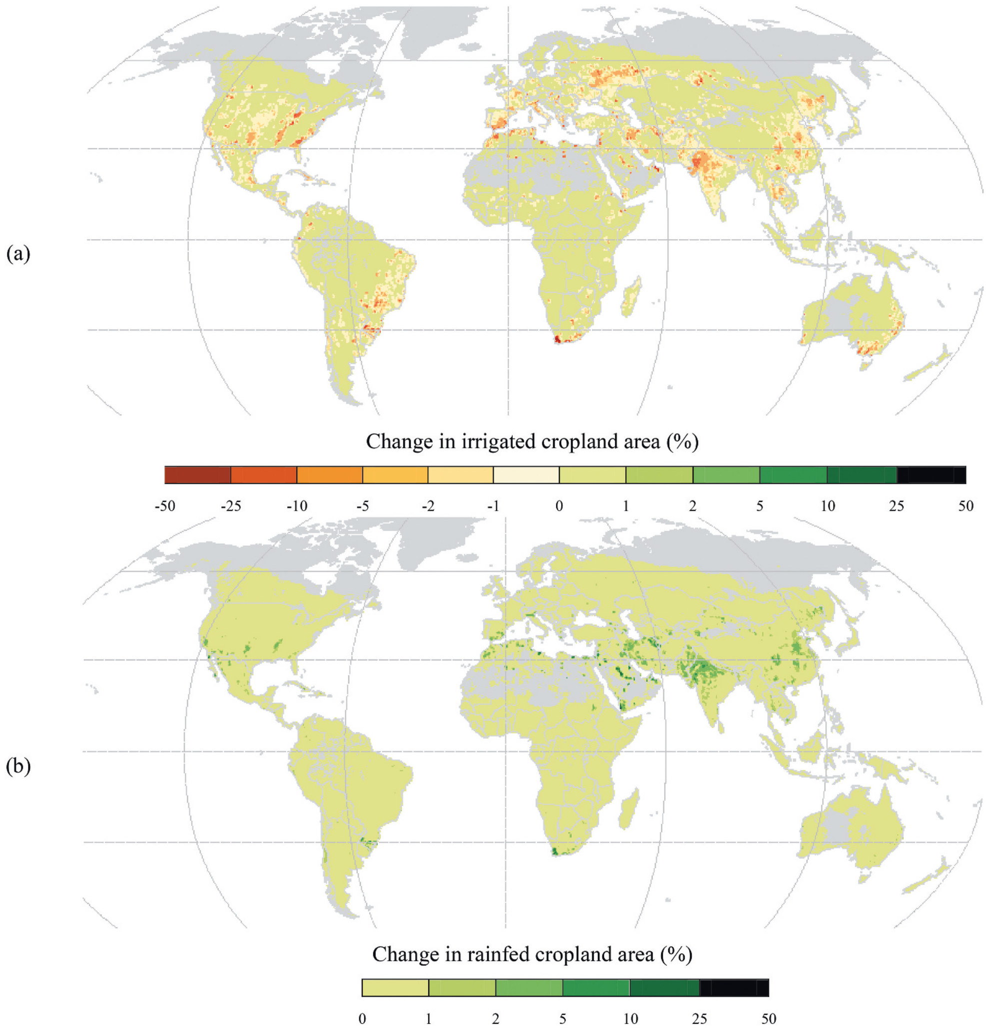

Figure 6. Global cropped area responses to global groundwater sustainability restrictions. (a) Percentage change in irrigated cropped area and (b) percentage change in non-irrigated (rainfed) practices as estimated by the SIMPLE-G model based on groundwater sustainability scenarios produced by the Water Balance Model (WBM). The maps illustrate the conversion to rainfed in targeted locations as for most of the grid-cells with large reduction in irrigated areas; a clear increase in rainfed areas is projected. Both maps show a moderate increase in irrigated and rainfed areas (light-green colouring). The expansion in global cropland area and conversion to rainfed are important channels of adjustment and economic responses to groundwater sustainability policy.

Impact on surface water

Figure 7 shows the spatial distribution of the impact of the groundwater conservation policy on surface water irrigation in percentage change. It shows an increase in surface water irrigation for almost all irrigated areas with the greatest increases in the hotspots of non-renewable groundwater use. As this is in percentage change, the magnitude of the change in surface water irrigation depends on availability and current uses. The increase in surface water irrigation reflects substitution of groundwater or a change in the location and scale of

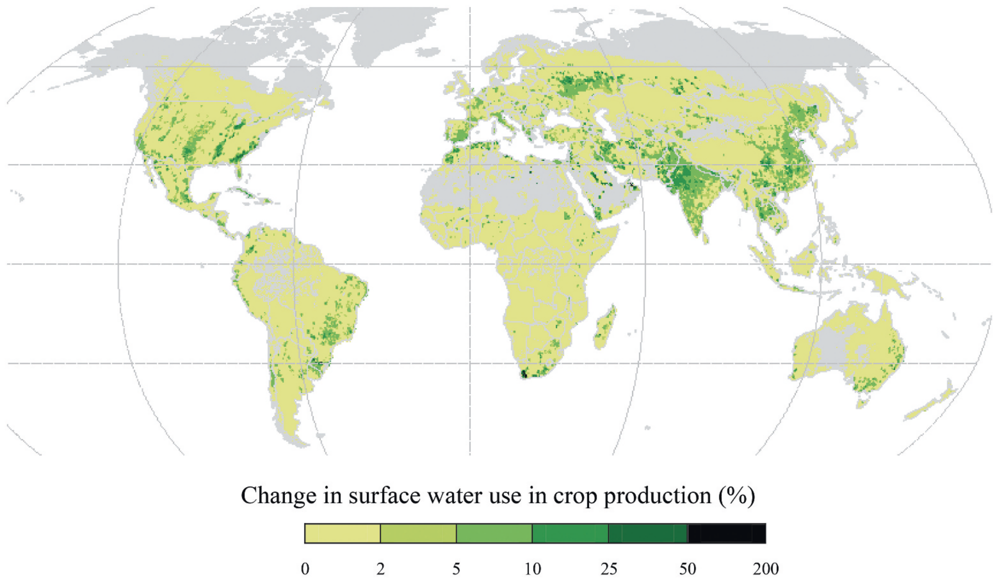

Figure 7. Global changes in surface water irrigation in response to global groundwater sustainability restrictions. The map shows the percentage change in surface water use in irrigation. The impact on surface water can be decomposed into a 'substitution effect' and a 'scale effect'. If the substitution 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 means an increase in surface water use with a dominant substitution effect; and light green colouring shows the locations where there is an increase in surface water irrigation due to a positive scale effect, absent the substitution effect.

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 targeted areas is positive and more than compensates for the decline in irrigated areas. If the scale effect is dominant (less irrigated area overall), the change in surface water use in the targeted area is negative. (The Appendix in the supplemental data online explores the extreme case wherein the expansion of the surface water irrigation is restricted in targeted areas.)

Impact on production

Figure 8 illustrates the impact of enforcing groundwater sustainable use on equilibrium irrigated and rainfed crop production. These 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 of unsustainable groundwater while rainfed production increases. The increase in surface water use in some dry locations may cause an increase in irrigated production next to the targeted areas or may not be enough to recover the irrigation production (look at the Middle East, for example).

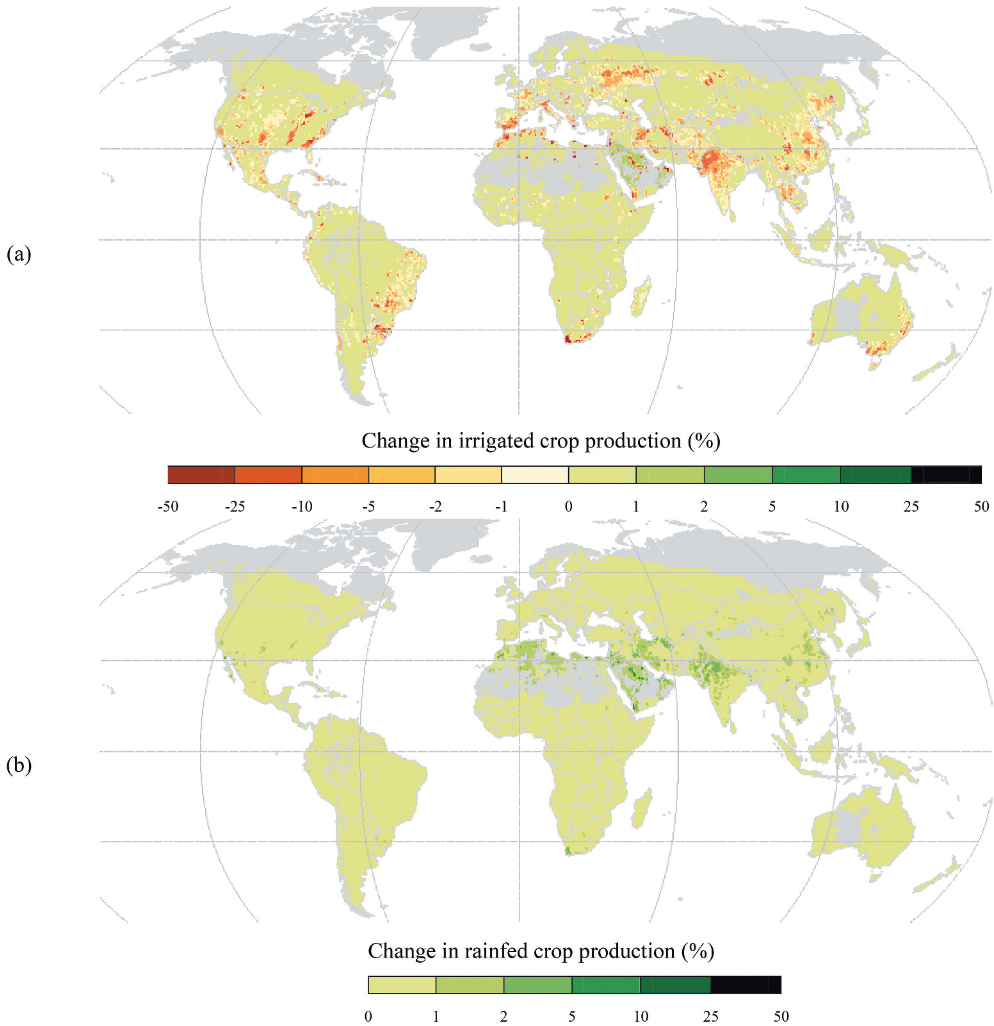

Figure 8. Global changes in crop production in response to global groundwater sustainability restrictions. The map shows the percentage change in (a) irrigated crop production and (b) rainfed crop production. Red and yellow colouring denotes a reduction in production and green colouring represents increases in production. While the irrigated production in the hotspots of unsustainable groundwater is substantially reduced, they show the biggest percentage increase in rainfed production. This conversion to rainfed agriculture compensates for some of the immediate impact on irrigated production. In addition, light green colouring on irrigated and rainfed maps indicate an expansion of crop production in non-targeted locations. While the patterns are similar to changes in cropped area, the percentage change in production is smaller, because rainfed crops have lower yields.

Regional outcomes

Restricting groundwater irrigation has diverse implications for regional crop production, land use and food prices. The long-run results at the regional scale are reported in Table 2 and the absolute changes are provided in Table 3. 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 those countries facing less severe restrictions, conversion to rainfed and surface water substitution (driven by higher local prices) can fully offset the decline in irrigated production.

In absolute terms, the biggest decline in crop production is predicted in China, India, the Middle East and North Africa by −12.5, −8.8, −3.6 and −2.5 million-ton change in crop production, respectively.

Table 2. Long-term regional impacts of restricting groundwater irrigation to renewable resources (percentage change in crop price, production and area, by region).

		Crop production (% change)			Cropped area (% change)%		
Region	Crop price (% 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%	−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	0.40%	−0.20%	−1.10%	0.40%	0.10%	−0.50%	0.20%

Source: Research findings based on SIMPLE-G.

Table 3. Long-term regional impacts of restricting groundwater irrigation to renewable resources (actual change in crop production and area, by region).

	Change in crop production (1000 MT)			Change in cropped area (1000 ha)		
Region	Total	Irrigated	Rainfed	Total	Irrigated	Rainfed
East Europe	889	−549	1390	146	−38	183
North Africa	−2497	−3241	738	53	−34	87
Sub-Saharan Africa	783	−568	1331	130	−13	143
South America	591	−747	1285	78	−16	95
Brazil	1108	−1628	2709	76	−40	117
Australia and New Zealand	129	−286	400	34	−9	43
Europe	39	−3303	3328	96	−80	176
South Asia	−8820	−15,781	6576	87	−541	628
Central America	−620	−1484	869	38	−37	74
South Africa	−1266	−1381	276	16	−25	40
Southeast Asia	−80	−2506	2381	69	−91	161
Canada	635	−20	617	55	−1	56
United States	−2983	−6100	3189	137	−190	327
China	−12,522	−24,971	11,874	98	−217	315
Middle East	−3581	−4992	1469	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	1209	−1404	2613

Source: Research findings based on SIMPLE-G.

Implications for virtual water trade

Groundwater restrictions are expected to alter the patterns of agricultural trade. 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. (Country-level results are reported in Table A6 in Appendix A in the supplemental data online.) The largest percentage declines in production are estimated to be 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 Table A6 online). In these countries, there is little possibility to use surface water to substitute groundwater (indeed, rivers in these areas are often over-abstracted), and there is little room for expanding rainfed agriculture at competitive production costs. On the other hand, 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 (Figure 6).

Table 4 shows the impacts of groundwater sustainability restrictions on 'virtual trade in blue water'. For all the regions, exports of virtual blue water decrease, with the biggest decline in the United States and South Asia. Note that this is largely due to the expansion of rainfed agriculture, both through conversion from irrigation as well as 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 paper. In summary, the groundwater and SW virtual trade will decline by 10.8 billion m^3.

Implications for employment

The employment is calculated assuming a gridded labour market with no labour mobility across grid-cells. Labour is part of the non-land composite input within a Leontief form

Table 4. 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	−0.1
Europe	−0.05	0.1	−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	0.4	−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

Source: Research findings based on SIMPLE-G.

Table 5. Impact of groundwater sustainability policy on virtual blue water exports by source.

	%		10^6 m^3	
	SW	GW	SW	GW
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	−2984
Central America	3.23%	−21.42%	239	−647
South Africa	6.30%	−28.41%	88	−141
South East 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%	3,271	−10,835

Source: Research findings based on SIMPLE-G.

for combining labour and other non-land inputs. Thus, the demand for labour input follows the changes in demand for non-land composite input due to changes in intensifications. Figure 9 illustrates the spatial pattern of change in employment. The pattern is slightly different from changes in cropped area and production. This is due to the differing contributions of non-land factors of production among countries. The initial numbers for gridded employment were obtained from subregional rates of labour per hectare of cropland. Section A6 in the supplemental data online provides more information on the average number of workers per hectare and per ton of corn-equivalent output in rainfed and irrigated agriculture.

Table 6 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 in the more extensive rainfed agriculture by 2.5 million jobs, creating a net gain of 1 million new jobs globally. Overall, these results suggest an increase more 0.5 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 the more extensive rainfed crop production which requires more labour to work the land. 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 non-land and land–water composites. As the land–water composite will be more scarce and costly, an intensification is expected which increases the average number of workers per hectare of land.

Theoretically, irrigated agriculture requires more labour per acre, because irrigating the same crop in the same location would require more labour. However, in some cases the regional average number of workers can be higher for rainfed agriculture compared with irrigated agriculture. There are several different reasons for this. First, irrigation is small in some regions, for example, in Brazil and Canada most of the crop production is

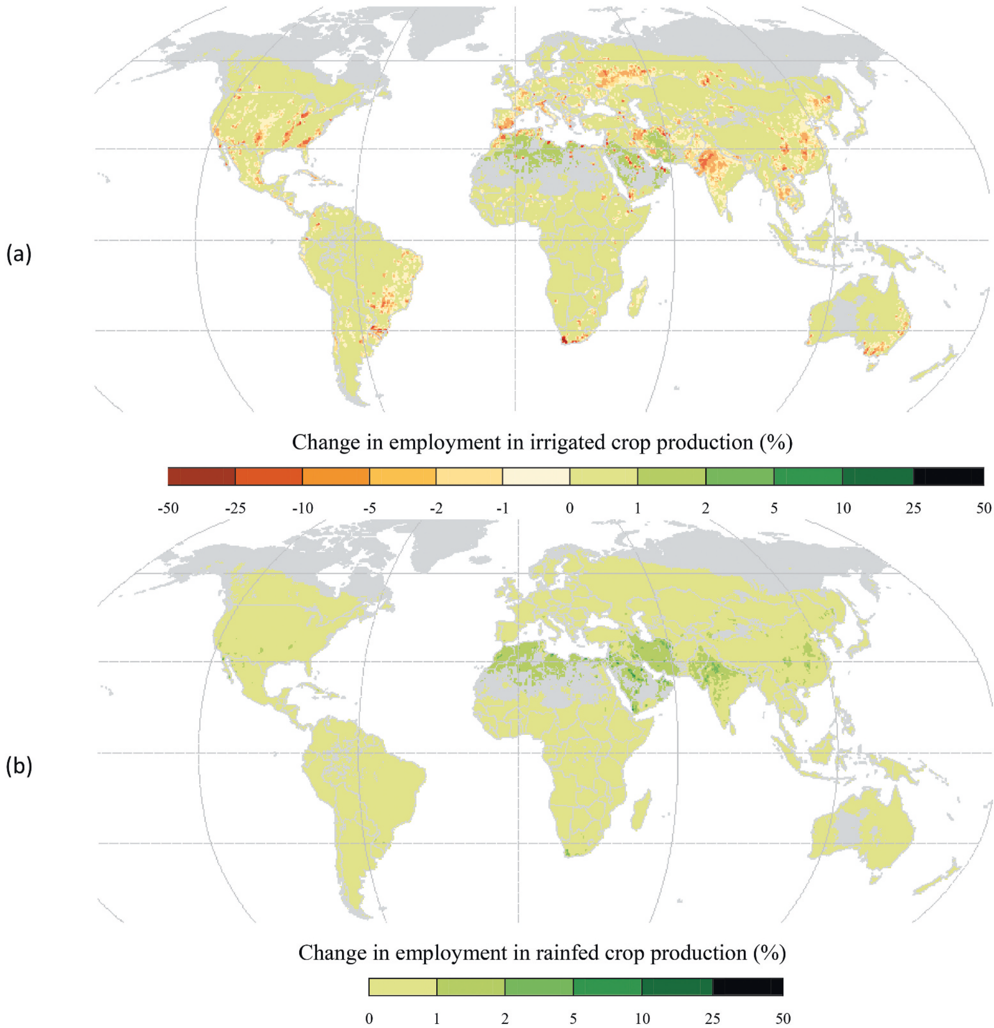

Figure 9. Global changes in agricultural employment in response to global groundwater sustainability restrictions. The map shows the percentage change in (a) employment on irrigated land and (b) employment on rainfed land. Red and yellow colouring means reduction in employment and green colouring represents increases in employment. While the patterns of change are similar to 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.

rainfed. Second, the crop composite can be different between irrigated and rainfed land within a region. For example, many labour-intensive hand-picked crops in Washington State, Florida, Michigan and Oregon are rainfed while corn is irrigated in parts of Nebraska with very low labour intensity. Thus, the outcome at the regional level depends on the significance of each crop and their labour intensity. Finally, more labour might be employed in rainfed production as farmers might decide to have more fertilizer and chemical application events to offset part of irrigation yield gap.

Table 6. Impact of groundwater sustainability policy on employment in crop production, by practice and region.

	% Change			Change in the number of jobs		
	Total	Irrigated	Rainfed	Total	Irrigated	Rainfed
East Europe	0.16%	−0.40%	0.25%	6107	−1979	8086
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	−1790	156,336
South America	0.18%	−0.15%	0.34%	7979	−2246	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	−4827	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	−7281	22,148
South Africa	0.31%	−1.73%	0.55%	2885	−1654	4538
South East 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%	4233	−2626	6863
China	0.14%	−0.41%	0.69%	296,608	−425,672	722,272
Middle East	0.52%	−0.16%	0.88%	46,601	−4980	51,581
Japan and Korea	0.06%	−0.01%	0.11%	662	−52	714
Central Asia	0.17%	−0.09%	0.36%	10,355	−2271	12,626
World	0.13%	−0.52%	0.50%	993,701	−1,424,400	2,418,129

Source: Research findings based on SIMPLE-G.

Interactions amongst the adaptation margins

Assessing the sensitivity of these findings to key parameter values reveals an interesting finding. The strength of any given individual margins 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. Or when substitution in trade is less possible, or conversion to rainfed is not feasible, 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 Figure 5 are quite sensitive to model parameters, the final impact on global production of this bounding analysis is less than 1% and the increase in price for more rigid assumptions is also less than 1%. The Appendix in the supplemental data online provides details about these sensitivity analyses and the interaction amongst the various adaptation margins.

Discussion and conclusions

Stress on groundwater is expected to increase due to income and population growth, along with global warming increasing agronomic water requirements. The rising number of drying wells and land subsidence around the world has increased attention to sustainable groundwater use (Befus et al., 2017; Jasechko & 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 land use and agricultural production implications of such a scenario.

Recent studies to evaluate 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 local impacts are largely ameliorated in the long run at the global level 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, the local impacts can be very significant for locations with a high dependency on unsustainable groundwater. The situation would eventually happen when they run out of water. The production and employment in some locations can decline by up to 90%. In locations without alternative sources for employment and food supply, this would have significant local impacts leading to over 1 million jobs lost and over 1 million families affected. And these local impacts will have adverse impacts on the broader economy – a point which 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 a national level (Calzadilla et al., 2010; Golub & Hertel, 2012; Liu et al., 2014).

The findings suggest that restricting groundwater irrigation could have a significant impact on local irrigated production in hotspots of non-renewable 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. The changes in relative prices at different scales will motivate changes in decisions and market outcomes. This includes compositional effects at the local level, changes in the location of crop production, changes in surface water irrigation, changes in irrigation extent, changes in irrigation intensity and changes in international trade of food commodities. Of course, these adjustments are costly and can cause environmental issues. Overall, the findings suggest that the land use and deforestation implications are small and 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 ha of cropland. The expansion coming from deforestation and cropping of marginal lands could lead to environmental degradation. In addition, as rainfed zones tended 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 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 virtual trade of blue water. Because of the likely changes in farmers' decisions and economic responses, it is necessary to consider wider market responses in evaluating the impacts of conservation policies. Global environmental and agricultural models that neglect the economic modelling of international trade may overestimate the production losses by not accounting for changes in exports and imports based on economic decisions.

Considering the socio-economic responses in the studies of impact analysis of sustainability policy will face another key challenge. While the sustainability issues are typically very localized, and thus require high-resolution land use and water use models, analysing the social responses and economic decisions at a fine-scale level is difficult due to lack of information. Unfortunately, to the best of our knowledge, there are few global models capable of high-resolution economic modelling. 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 individual grid cell level, rather it is applied to representative groupings of grid cells – making analysis of local responses to sustainability restrictions more challenging. Similarly, the Global Change Assessment Model provides a framework for modelling groundwater resources and land use, deploying a range of supply- and demand-driven adaptive responses (Turner et al., 2019a, 2019b), but is implemented at the river-basin level. However, high-resolution analysis is important due to heterogeneity of land and water use among grid-cells within aquifers (for example, the sustainability restrictions and responses would be different between Northern Plains and southern regions of Ogallala aquifer in the United States). Here, SIMPLE-G introduces one of the first frameworks capable of modelling 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 with it 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. That route will eventually generate far more severe local (and global) consequences. Intervening to restore stability, which we have endeavoured to model in this paper, reduces the *average* water available from groundwater but crucially preserves the flexibility and emergency buffer resource 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 is 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, the 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). So by incurring negligible production loss today, countries can keep their resource for the time most valuable. This opens a further route for future research.

In closing, this paper has provided some 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 the farmers are adjusting their decisions based on market outcomes, there can be a high reduction in local production, employment, and farm income. We do find that aggregate employment will increase in the long run. This assures communities with sustainable water use will avoid the risk of running out of groundwater in the time most needed.

Disclosure statement

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ORCID

Iman Haqiqi http://orcid.org/0000-0001-7331-4615
Chris J. Perry http://orcid.org/0000-0002-9003-7477
Thomas W. Hertel http://orcid.org/0000-0002-7179-7630

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