Chapter 12
Local Groundwater Sustainability Policies and Global Spillovers

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1 Introduction

The Simplified International Model of agricultural Prices, Land useLand use, and the Environment-Gridded version (SIMPLE-G) is a quantitative framework that allows for global-to-local-to-global (GLG) analysis of a broad range of environmental research topics. The philosophy of this multiscale, GLG approach is to evaluate the long-run implications of global changes for local environmental stresses and assess the implications of local responses for global conditions through global and regional agricultural markets. In this chapter, we focus on groundwater sustainability as an application of this GLG framework. First, we look at the local changes in water withdrawal caused by global drivers using a decomposition approach, which allows us to quantify the separate contribution of global economic changes to growth in irrigation water withdrawal in the United States. We look at population and income

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

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as demand-side drivers and growth in total factor productivity (TFP, the ratio of outputs to inputs) as a supply-side driver. Second, we quantify changes in crop production and agricultural water and land use around the world in response to local groundwater sustainability policies in the United States. This research highlights the trade-offs between economic production and sustainability as well as the unintended consequences of local sustainability policies, including the associated spillover effects. This multiscale framework can better inform local environmental policy by providing a holistic evaluation.

1.1 Motivation

Groundwater is a crucial resource for many communities worldwide, supplying water for drinking, irrigation, and industry. In recent decades, rapid economic growth has intensified the impacts of human systems on natural ecosystems, with degraded land and water resources creating a global crisis (Jury and Vaux Jr. 2007; Hanjra and Ejaz Qureshi 2010; Srinivasan et al. 2012; Famiglietti 2014). Rapid groundwater depletion is among the most challenging of these environmental problems (Changming et al. 2001; Qureshi et al. 2010; Karami et al. 2012; Konikow 2013; Voss et al. 2013; Castle et al. 2014; Liesch and Ohmer 2016; Dalin et al. 2017; Nabavi 2018). The pressure on farmers to produce more output has led to unsustainable use of water resources in many locations (Seckler et al. 1999; Faunt 2009; McGuire 2017; Reitz et al. 2017; Russo and Lall 2017; Rodell et al. 2018).

Groundwater overexploitation can result in several challenges, including increased pumping costs because of declining groundwater levels. This can lead to a rise in costs for farmers, households, and businesses. Moreover, overexploitation can cause water quality degradation due to saltwater intrusion and other issues, which can increase the costs of treating water for drinking and other purposes. Land subsidence, which is another problem that can arise due to groundwater overexploitation, can cause damage to infrastructure and reduce property values and the availability of water for ecosystems, leading to a loss of ecosystem services (e.g., water filtration and flood control). In extreme cases, if groundwater wells become completely depleted, it may be necessary to explore options such as relocating individuals, farmers, and businesses or implementing water transfer initiatives.

In addition, reductions in groundwater storage threaten many regions' ability to meet future water needs (Cook et al. 2015). Groundwater demand is likely to be particularly strong in the coming decades, as irrigation becomes a more important element of agricultural adaptation in a warming climate (Perry et al. 2009; Schlenker and Roberts 2009; Nepal and Shrestha 2015; Pathak et al. 2017; Haqiqi 2018; Haqiqi et al. 2019, 2021).

1.2 Other Studies

Given the importance of future groundwater sustainability, a variety of different approaches have been employed to study the interactions between hydrological and human systems. The growing literature in sociohydrology involves using increasingly complex models to address challenges involving water quality, groundwater depletion, flood risk, drought, and conflicting demands (Ertsen et al. 2014; Ghosh et al. 2014; Van Emmerik et al. 2014; Fernald et al. 2015; Blair and Buytaert 2016; Giuliani et al. 2016; Di Baldassarre et al. 2019). The literature on telecoupling and virtual water trade has also explored the connections between human systems and land–water systems (Dalin et al. 2012; Bruckner et al. 2015; Wichelns 2015; Chaudhary and Kastner 2016; Hertel 2018; D'Odorico et al. 2019). However, the significance of global drivers of local sustainability stresses (e.g., changes in groundwater withdrawals) has not previously been quantified in a multiscale, economic equilibrium framework.

1.3 SIMPLE-G Contribution: Spillovers

Effective water sustainability policies require an understanding of the critical interactions between environmental and human systems. Decisions and policies in the human system can affect the environment, but changes in the environment can also affect people and their decisions. Solutions and strategies ignoring these responses may fail. For example, improving irrigation efficiency can result in increased irrigation demand motivated by lower costs (Perry et al. 2017; Grafton and Wheeler 2018; Perry 2019; Pérez-Blanco et al. 2020). Groundwater policies and changes in the groundwater table can have spillover effects, either positive or negative, and can impact a diverse group of stakeholders. It is crucial to consider the potential spillover effects of these policies and changes in the groundwater table when making decisions related to groundwater resource management.

While food security issues are typically studied at the global and country levels, resource sustainability stresses are usually felt at the local level (e.g., abandoned villages, dying wells, drying lakes and subbasins, and land subsidence). The overarching goal of this chapter is to measure how economic changes in one region can affect environmental sustainability in another region of the world as well as how the implementation of local sustainability policies can export environmental stresses to other regions. Such connections in the global food system can have important implications for global environmental justice as rising incomes in some regions support increasingly rich and specialized diets, resulting in significant environmental costs elsewhere (e.g., Harrison 2011; Marston et al. 2015).

This study also contributes to the literature on international trade in virtual water and virtual land by quantifying the impacts of population changes on remote water and land resources (Hoekstra and Mekonnen 2012; Hoekstra and Wiedmann 2014; Ramankutty et al. 2018).

The model of this study is built on previous economic studies with valuable insights on commodity trade (Armington 1969), food security (Hertel and Baldos 2016), water and food (Liu et al. 2014), water and trade (Liu et al. 2017), land allocation (Ahmed et al. 2008), irrigation demand (Haqiqi and Hertel 2016), value of water (Haqiqi 2023), water rights (Jame and Bowling 2020), water stress (Roath 2013), and groundwater (Befus et al. 2017). This study extends the previous modeling work of Baldos et al. (2020) by incorporating a new land allocation framework to improve the modeling of land-use changes at each location (Zhao et al. 2020).

1.4 Limitations

To focus on the decomposition of the impacts of global changes, we do not consider changes in water and heat stress due to climate change. We are aware that this simplification is likely to result in the underestimation of future water stress in many regions by midcentury. However, this simplification allows us to focus more sharply on the main messages of the study, namely, the importance of global–local–global linkages in the context of land and water sustainability.

2 SIMPLE-G Version Employed for This Application

In this application, we focus on the groundwater module of SIMPLE-G (Fig. 12.1) to analyze economic decisions about groundwater withdrawals for irrigated cropland and its responses to global and local changes. These withdrawals are defined as the amount of water extracted from groundwater resources; this amount is usually greater than crop groundwater consumption, with the difference recharging groundwater or running off into streams.

2.1 Determinants of Groundwater Withdrawal

The variables affecting withdrawal decisions vary and include surface water availability and costs, groundwater availability and costs, irrigation extent, irrigation rent gaps, irrigation infrastructure (equipment and technology), crop prices, and crop production technology. When modeling groundwater withdrawals, hydrological models usually consider crop water requirements, irrigation extent, and irrigation efficiency while ignoring economic decisions.

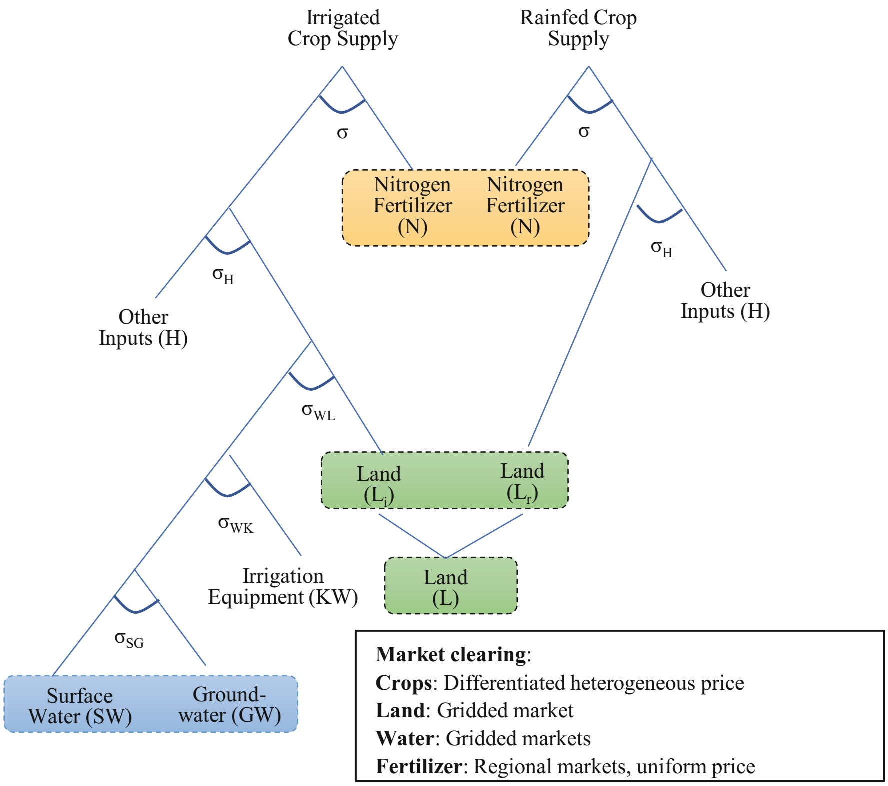

Fig. 12.1 Structure of crop production at each grid cell
Shocks and policy variables are defined for surface water, groundwater, irrigation equipment, land, nitrogen fertilizer, and overall crop production

In SIMPLE-G, both the economic and hydrologic components of water resources are considered. While hydroclimatic sources are exogenous drivers of the changes, the economic forces are endogenously modeled. In this framework, the availability and cost of surface water play determining roles, as farmers tend to withdraw less groundwater if surface water is readily available and less expensive. The cost of pumping groundwater is another factor influenced by the depth of the aquifer, the type of pumping equipment used, and energy costs. The extent of irrigation is endogenously determined in SIMPLE-G and affects the economic demand for water, while irrigation rent gaps and irrigation yield gaps can incentivize farmers to expand irrigated areas. In SIMPLE-G, using efficient irrigation equipment and technology can help reduce groundwater withdrawals. Crop prices and production technology are other variables that can impact groundwater withdrawals. Government policies, climate change, population growth, and economic development can also affect groundwater withdrawals in the model. Groundwater management regulations are one example of government policy that can influence groundwater withdrawals; others include energy, agriculture, or trade policy. Climate change affects groundwater resources in various ways. It can result in changes in rainfall patterns that affect hydrological supply (i.e., availability), and changes in temperature will alter agronomic crop water demand, which can result in increased groundwater withdrawals and decreased surface water availability. Population growth and economic development also increase demand for water resources through increases in food demand.

2.2 Decomposition

The significance of these factors varies based on the specific circumstances of each region. Therefore, it is essential to consider all these factors when developing policies for sustainable groundwater resource management. A key feature of our analysis is decomposition, which we provide with respect to the exogenous drivers of sustainability stresses. We follow the numerical integration approach developed by Harrison et al. (2000) to decompose the contribution of each exogenous variable to changes in output variables. Exogenous variables include global population growth, economic developments, technological progress, weather, and policies.

2.3 Land Allocation

In this application, we incorporate the quantity-preserving land allocation framework to improve the modeling of land-use changes at each location (Zhao et al. 2020), as described in Model 4 (see Chap. 5). This framework is particularly appropriate because we expect to see cropland converted from irrigated to rainfed uses, and vice versa when demand for groundwater is altered. The new approach ensures that we preserve the physical area as opposed to the economic volume.

2.4 Product Differentiation

Additionally, we employ product differentiation or the subregional relocation module to improve the modeling of changes in patterns of agricultural activity across grid cells and crop production zones defined by the USDA Farm Resource Regions (FRR), treating crop commodities from each FRR as differentiated commodities. This allows us to capture the tendency of crops to shift, first and foremost, within the same FRR (e.g., the Fruitful Rim).

2.5 SIMPLE-G Database Version

This application utilizes a comprehensive gridded dataset based on the reference year of 2010. To ensure consistency with SIMPLE-G, we aggregate all crops into one composite category by weighting crop outputs by relative prices. The resulting database contains detailed information regarding agricultural production and input costs for approximately 75,000 grid cells throughout the United States. This approach allows us to capture a greater level of detail regarding agricultural production and input costs and account for regional and local variations. Compared to national- or state-level models, this gridded dataset provides a more accurate and comprehensive understanding of agricultural production and input cost distributions in the United States, which is essential for effective policy-making and resource allocation.

3 Experimental Design

Two experiments are considered here. First, we integrate relevant factors anticipated to shape the future of land and water use, such as evolving population dynamics, shifting income, and technical growth (Baldos and Hertel, 2013). Second, we introduce a specific policy intervention that serves as the focal point of our sustainability analysis, allowing us to assess the impacts on agriculture.

3.1 Global Change Scenarios

Table 12.1 presents key elements of our global change scenario. In this scenario, we consider changes in population and income, as in Baldos and Hertel (2014), based on the business-as-usual shared socioeconomic pathway 2 (SSP2) from 2010 to 2050. Regarding productivity, we assume that the historical rates of productivity growth persist to midcentury (Fuglie 2012) and apply uniform cumulative TFP growth in the processed food sector. Here, TFP growth shows how much more production is possible using the same volume of inputs.

The purpose of this exercise is not to provide comprehensive future projections but rather to disentangle the significance of global drivers of local stresses within a GLG framework. The change in income, population, and TFP provides a regionally heterogeneous pattern of demand and supply shocks. Given different values of behavioral parameters, the outcome of these shocks can be quite complicated. Thus, we perform a decomposition to evaluate the significance of each driver considering GLG linkages.

Table 12.1 Projected percentage changes in population, income, and productivity, 2010–2050

Region	Population	Income per capita	Crop TFP	Livestock TFP
Eastern Europe	−12.7	239.5	17.6	50.0
North Africa	44.0	224.7	42.2	17.7
Sub-Saharan Africa	139.4	401.0	17.9	17.7
South America	31.1	176.3	132.8	157.0
Australia	33.8	70.7	64.2	17.7
Europe	0.0	66.3	78.6	17.7
South Asia	40.8	640.6	83.3	96.0
Central America	41.2	154.6	115.4	157.0
South Africa	16.0	239.5	26.8	17.7
Southeast Asia	32.1	363.6	47.0	157.0
Canada	25.8	56.4	71.1	17.7
United States	25.0	58.6	71.1	17.7
China	−6.3	606.7	121.7	157.0
Middle East	65.2	102.6	41.5	17.7
Japan + Korea	−14.5	97.6	75.0	17.7
Central Asia	52.3	394.2	25.2	50.0

Productivity is measured by growth in TFP
Sources: Percentage changes in population and income are obtained from Baldos and Hertel (2014) aggregated to 16 regions from country-level information based on SSP2 (O'Neill et al. 2014). The changes in productivity are calculated based on Fuglie (2012). The cumulative rate of productivity growth in the processed food sector is 42% worldwide

3.2 Local Sustainability Scenarios

In addition to the global-to-local analysis, we also evaluate the global impacts of a sustainable groundwater policy for the United States (i.e., the local-to-global linkages). Here, the sustainability policy is defined as restricting groundwater withdrawals to the rate of groundwater recharge in unsustainable grid cells across the United States. The data on extraction and recharge rates used in this study are obtained from the US Geological Survey (Reitz et al. 2017). We first constructed a ratio of groundwater extraction to recharge at each location circa 2010. As the year 2010 was a relatively wet year with abnormally high recharge rates, the 2010 ratio likely underestimates the long-run sustainability stress. Therefore, we use a 5-year average over 2007–2012 to calculate the ratio of groundwater extraction relative to local groundwater recharge by 5 arcmin grid cells circa 2010. We base the shocks to the groundwater supply module on this ratio (Haqiqi, 2023).

The appropriate experimental design for any given study will benefit from multidisciplinary collaboration and discussions. To design a groundwater sustainability policy, a multidisciplinary scientific collaboration mechanism should include—at minimum—economists, agronomists, and hydrologists. Economists can provide insights into the economic aspects and likely impacts of groundwater conservation policy, while hydrologists can offer insights into the required intensity of sustainability restrictions considering groundwater aquifers' physical characteristics, the hydrological impacts of changes in withdrawals, and the potential for recharge. Agronomists can assess the impact of restricting water availability throughout the growing season. Policymakers and scientists from other disciplines can provide additional insights into the applicability or acceptability of proposed conservation scenarios.

The goal of this application is to provide insights into the unintended consequences of possible groundwater conservation policies. The SIMPLE-G framework can provide a more comprehensive and informed understanding of the spillover effects of local groundwater sustainability solutions. To construct a comprehensive scenario, it is necessary to engage with a wider range of stakeholders. This approach can help to ensure that the policy design process is more spatially inclusive and that the ensuing adverse impacts do not exceed the policy's benefits.

4 Results

This section presents the findings of our investigation into the potential impacts of the two scenarios, utilizing the SIMPLE-G-US model solved in GEMPACK as our modeling framework. Focusing on two key metrics—agricultural production and groundwater withdrawals—we analyze plausible future conditions to assess their impact on water resource sustainability. The results reveal how production levels and groundwater use might shift based on policies and assumptions about population growth, economic development, and technological change, offering valuable insights for water management strategies.

4.1 Global to Local Analysis of Groundwater Demands

The global change scenario includes changes in income per capita, population, and TFP along a business-as-usual pathway from 2010 to 2050 for which key drivers are shown in Table 12.1.

4.1.1 Global Decomposition

The results of this scenario suggest that the changes in income and population, taken on their own, boost equilibrium crop production and input use (i.e., land, water, and fertilizer). However, global TFP plays a critical role in offsetting a major portion of the pressure from income and population growth on agricultural inputs. For example, changes in population and income alone would increase global cropland by around 29.91% (13.27% + 16.64%), while TFP is projected to reduce global cropland by 22.99%, leading to a far more modest 7.14% final increase in cropland in this scenario. This reveals the significance of TFP as a tool for reducing stress on global land and water resources (recall the discussion of TFP in Chap. 10).

4.1.2 Regional Decomposition

Figure 12.2a shows the major drivers of production change by region. It also decomposes the projected contribution of each driver to this aggregate outcome. In the United States, production is projected to rise by nearly 50% or roughly 0.4 billion corn-equivalent metric tons, valued at US$97 billion (in 2010 prices), over this four-decade period. The drivers of US crop output growth are relatively evenly divided between both domestic and foreign (red bar) increases in population, rising per capita incomes around the world (green bar), and improved productivity in global crop production (blue bar). In Eastern Europe and China—regions with little projected population growth (red bar)—income is the main driver of crop production (green bar). Income growth is also a key driver of output growth in South Asia, while population growth is the most important food demand driver in Africa. Note that global productivity growth has a negative impact on output in Central Asia, South Africa, Sub-Saharan Africa, and Eastern Europe. This is mainly caused by a loss in competitiveness due to low productivity growth in these regions compared with the rest of the world.

Although productivity growth leads to higher yields and therefore moderates the demand for land, the impact of population and income growth on land use is dominant in all regions except for Europe. Sub-Saharan Africa (+120 Mha) and South Asia (+36 Mha) are projected to experience the largest increases in cropland due to strong domestic demand growth in those two regions. Our analysis indicates that growth in income and population outside the United States is far more important in driving US crop production (contributing to a 22.3% increase) than income and population growth within the United States (contributing just a 6.6% increase). This is due to higher income growth rates in developing and emerging economies and higher rates of population growth in Africa and other low-income regions. For details on the regional decomposition of the global drivers of changes in water, land, and fertilizer inputs, see Haqiqi et al. (2023).

Figure 12.2b illustrates the drivers of change in US groundwater withdrawals in more detail. The greatest impacts on US groundwater are from population increases in the United States, South Asia, and Sub-Saharan Africa as well as income growth in Sub-Saharan Africa, China, and South Asia. US TFP growth—makes US agriculture more competitive—also contributes to increased US groundwater withdrawals. However, global TFP growth offsets the impacts of increased income and population.

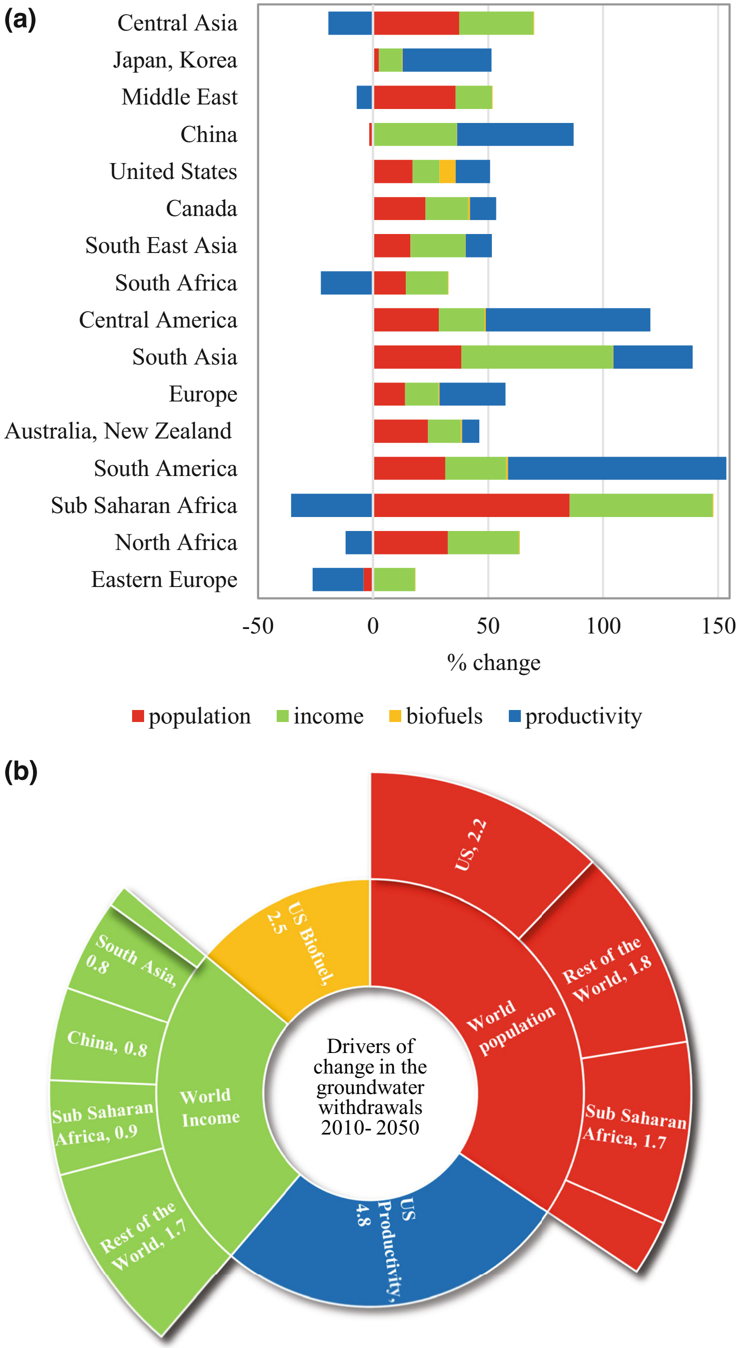

Fig. 12.2 Change in (**a**) crop production by region and (**b**) US groundwater withdrawals, 2010–2050
(**a**) Decomposition of changes in regional crop production from 2010 to 2050 due to the combined effect of changes in per capita income, population, and technology, around the world, as well as

4.1.3 Local Decomposition

Figure 12.3 illustrates the pattern of changes in groundwater withdrawals and irrigated areas across the United States due to a population increase of one million people in each world region. These changes are calculated by dividing the computed contribution of population change in each global region by the population change headcount in that region. For example, if the model calculates that an increase of *Y* people in region *r* has caused an *X* hectare change in irrigated area in subregion *z*, then the average impact of a change in population in region *r* on irrigated area in subregion *z* is equal to X_z/Y_r. We perform similar calculations for cubic meters of water. The general finding is that normalized population changes in Canada and Europe will have greater contributions to changes in water withdrawal and irrigation contraction—four times greater than those in China—for a given size of population change. Note that the population change in any region has a direct relationship with water and irrigation in the United States. Thus, a decline in population, in China, for example, means less stress on land and water resources in the United States. Another general finding is that most of the changes occur in the Fruitful Rim and Basin and Range in the Western United States. Finally, a one-million-person increase in world population can increase irrigated area in the United States by 100–400 ha depending on the source of population growth.

There are two major observations at the grid-cell level. First, the most rapid irrigation expansion (in percentage terms) is expected to occur in the Eastern United States. This finding is in line with current observations showing rapid irrigation expansion in the East and declines in the West during the 1997–2017 period (USDA 2019; Xie et al. 2021). Second, foreign demand drivers of groundwater withdrawals are more important than US demand drivers. SIMPLE-G can also be employed to provide economic insights into the likely impacts of changes and unintended consequences of policies for water and land resources—a topic to which we next turn.

4.2 Local-to-Global Analysis of US Groundwater Sustainability Policies

We implement the sustainability policy by reducing groundwater withdrawals to the rate of recharge (for details, see Haqiqi et al. 2023). To achieve this, we apply a shifter to the groundwater supply curve. This is accomplished by shocking the

Fig. 12.2 (continued) growth in biofuels demand. (**b**) Decomposition of drivers of changes in US groundwater withdrawals from 2010 to 2050 as computed by SIMPLE-G-US-Allcrops, based on SSP2 (Shared Socioeconomic Pathways, middle of the road) in the absence of climate change. Improvement in global productivity can completely offset the impacts of increased population and income, conditional to sufficient investments. Also, the rebound effect causes an increase in groundwater withdrawals

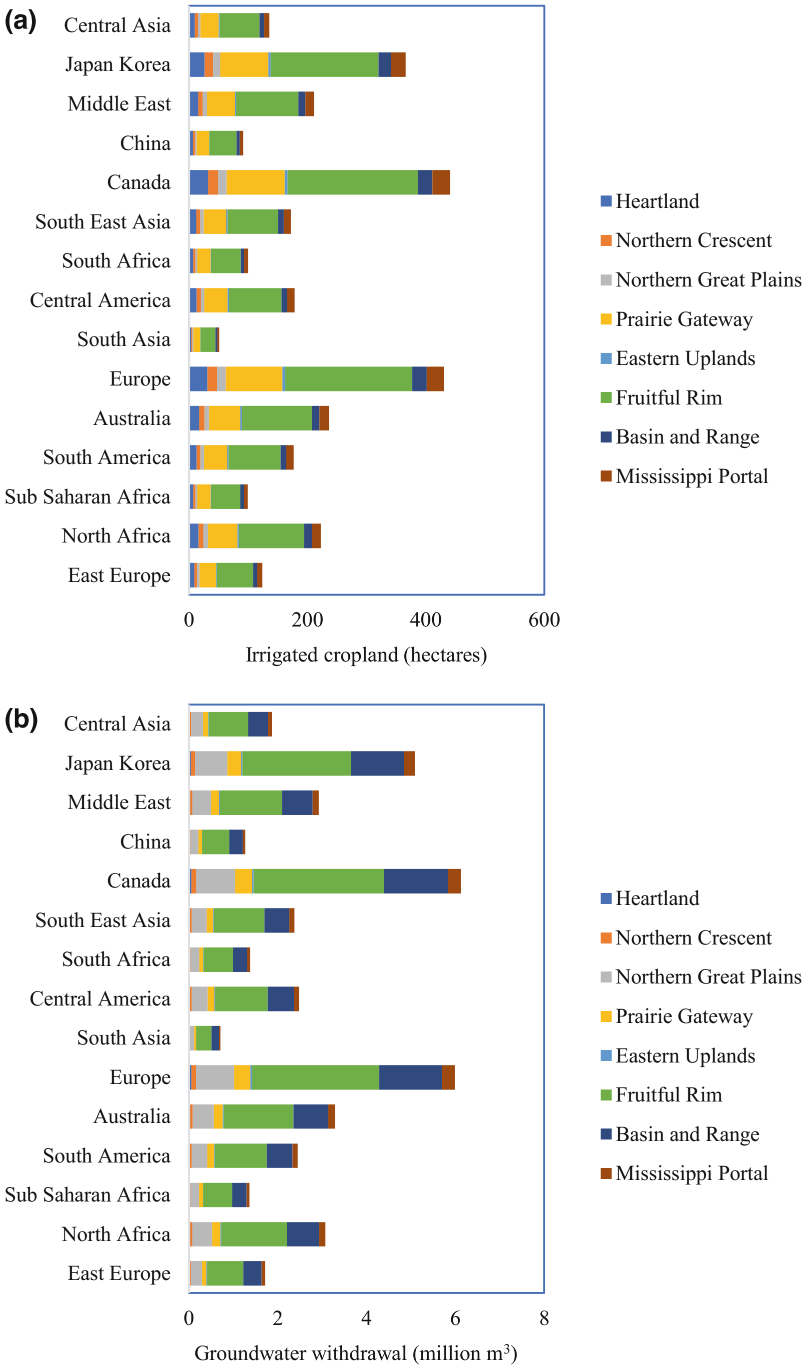

Fig. 12.3 Change in (**a**) US irrigated land and (**b**) US groundwater withdrawals in response to a population increase of one million, by region
Uniform population increases/decreases in Europe, Canada, Japan, and Korea have larger impacts on water and land resources in the United States than population increases/decreases elsewhere. A decline in the population of these regions can cause a bigger decline in cropland in the United States. In general, impacts on the western regions (Fruitful Rim, Basin, and Range) are largest

appropriate slack variable in the model code. The size of this shock indicates the amount of reduction required from 2010 levels to ensure that the rate of withdrawal does not exceed the recharge rates. If a grid cell is extracting groundwater at a rate higher than the recharge rate, it must reduce withdrawals. To ease the implementation of these shocks, we truncated them at −90%, so we do not wholly eliminate groundwater use in any grid cells.

Out of the approximately 75,000 grid cells, this policy will have a direct impact on 10%, all of which are located in the Western United States. These grid cells face a significant reduction in groundwater availability, ranging from −1% to −90%. More than half of these cells will experience a reduction of more than 80%. The strict policy will cause some agricultural activities to relocate to other parts of the country that have abundant water resources and that are already major agricultural producers. However, these regions may not be able to accommodate all of the agricultural activities displaced from the Western United States, leading to increased production overseas.

4.2.1 Local Impacts and Spillovers

At the local level, the first response to this policy is a reduction in groundwater withdrawals. Figure 12.4a shows the resulting change in groundwater withdrawals by grid cell. Green areas require groundwater withdrawal reductions of more than 50%. This change induces an increase in groundwater withdrawals elsewhere in the United States. The greatest increase in groundwater withdrawals occurs in the southern and eastern parts of the Fruitful Rim region, which includes Texas and Florida, which have appropriate agroecological conditions for producing crops similar to those produced in California (the targeted regions).

The groundwater restriction scenario is expected to increase the shadow price (marginal value of water to the producer) of water by more than 50% in the targeted regions. This raises the average crop production cost by 9–15%. Figure 12.4b shows the projected change in the equilibrium price (value) of groundwater in the United States. For the targeted regions, this increasing scarcity value is mainly due to a lower supply of water. However, for other parts of the United States, the increase in the groundwater shadow price is due to changes in the demand for irrigation.

Another potential local response to this groundwater sustainability scenario is to increase the use of surface water, as this approach offers a potential substitute—albeit an imperfect one—for groundwater. It is not considered a perfect substitute: The regulations and the extraction methods are different, and farmers may not have the same control over the timing of water availability. Figure 12.5a shows the estimated change in US gridded surface water withdrawal in the wake of the groundwater sustainability policy. Depending on water availability and institutions, surface water withdrawals might increase from 5% to more than 25% in nontargeted parts of the United States. The surface water withdrawal is projected to decline in the restricted grid cells due to large reductions in the irrigated area (Fig. 12.5b). While the global response is small, the base over which this applies is large, so if the US

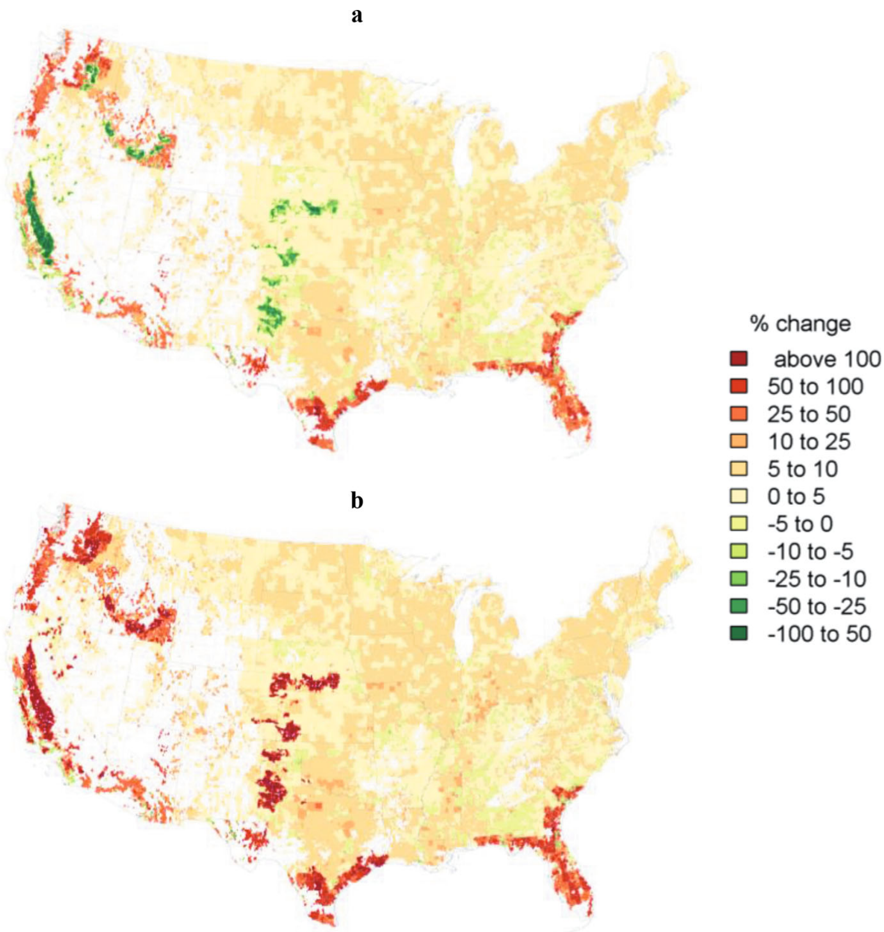

Fig. 12.4 Percentage change in (**a**) groundwater withdrawals and (**b**) value (shadow price) of groundwater to producers by 5 arcmin grid cells in response to a policy restricting groundwater withdrawals to the level of average annual recharge
Areas in *white* are not cultivated

cropland area declines by 1 million hectares, the global cropland area increases by 2.3–2.5 million hectares in response to US groundwater restrictions. This reflects the extremely high yields on US irrigated croplands which must be replaced by production elsewhere to meet global food demands, which are only slightly reduced in the face of higher prices.

4.2.2 Global Impacts

Figure 12.6a reports the estimated percentage change in global cropland area—less than 1% in each region—due to US groundwater sustainability restrictions. This

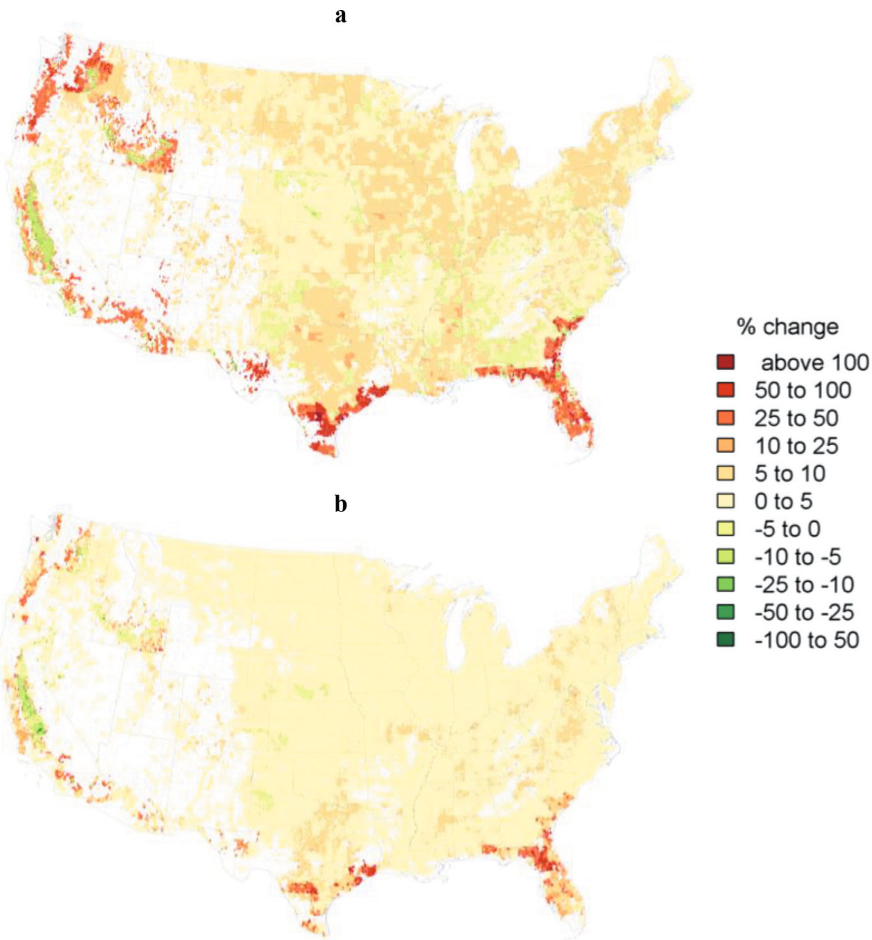

Fig. 12.5 Percentage change in (**a**) irrigation surface water withdrawals and (**b**) total cropland area by 5 arcmin grid cells in response to groundwater restrictions
Areas in *white* are not cultivated

experiment shows that local sustainability solutions may be viewed less favorably in a global context. The unintended consequences include possible deforestation (increase in cropland) and water quality issues (higher fertilizer applications) in nontargeted areas. This shows why we need to take a global approach to evaluating water policies to consider significant feedback from the human system to natural resource use when designing effective and efficient sustainability policies (Biswas 2008).

Table 12.2 depicts the impacts of US groundwater sustainability restrictions on the world and the United States. It is projected that this local groundwater sustainability policy may lead to a 0.1% increase in global cropland area (1.7 million hectares) and a 0.3% increase in fertilizer application worldwide. In the United

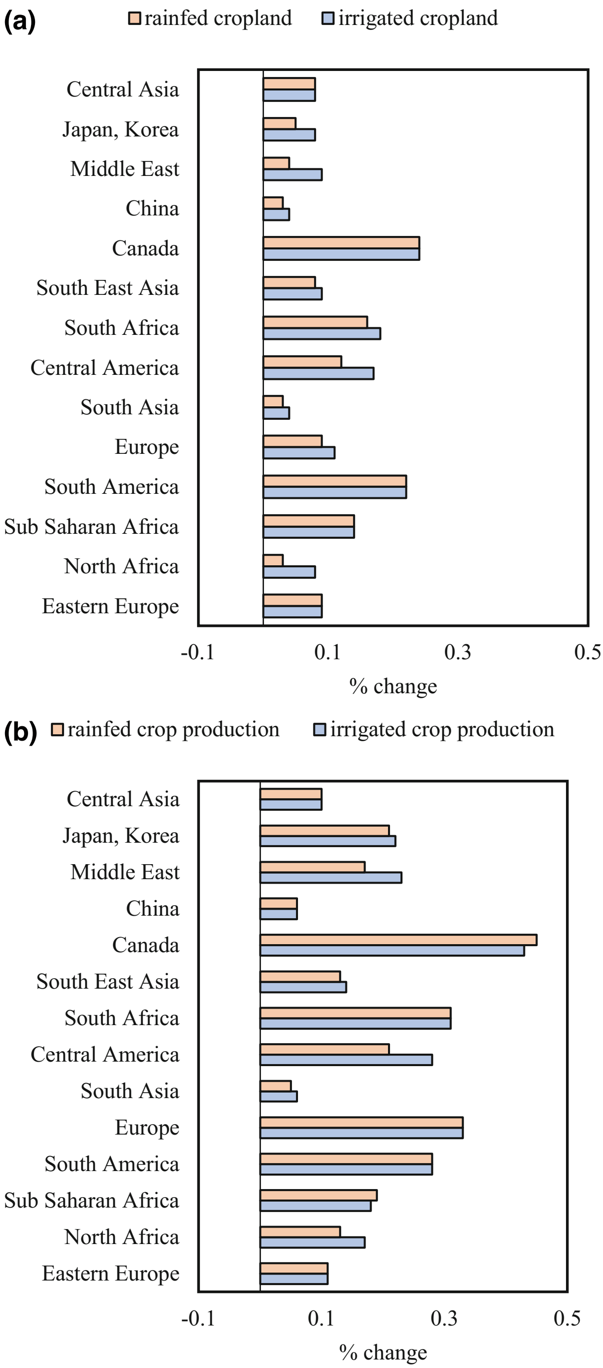

Fig. 12.6 Percentage change in (**a**) global production and (**b**) land use in response to a US groundwater sustainability constraint in 2050

Table 12.2 Projected changes in cropland area, water withdrawal, fertilizer applications, and crop productions in response to US groundwater restriction

	World			US		
	Irrigated	Rainfed	Total	Irrigated	Rainfed	Total
%						
Crop production (%)	−1.03	0.61	−0.06	−16.39	5.37	−2.98
Cropland area (%)	−0.35	0.23	0.11	−4.68	1.18	0.13
Surface water withdrawal (%)	1.36	na	1.36	4.19	na	4.19
Groundwater withdrawal (%)	−9.25	na	−9.25*	−61.70	na	−61.70
Fertilizer application (%)	−0.32	0.39	0.25	−11.01	4.50	1.46
Δ						
Crop production (m ton)	−46.07	39.32	−6.77	−50.91	28.97	−21.93*
Cropland area (m ha)	−1.12	2.82	1.70	−1.33	1.54	0.21

(* See application files for more details)

States, the irrigated area declines by 4.7%, leading to a 16.4% reduction in irrigated production (50.9 million tons corn-equivalent). The responses within the United States are estimated to increase rainfed areas (extensive margins) and fertilizer application in rainfed areas (intensive margins). This is mainly due to a 9.4% increase in local crop prices in Fruitful Rim, which will motivate other farmers to increase their production and new farmers to enter the market. A model closure with low local production flexibility could increase the non-US cropland area by up to 20 million hectares. For detailed analysis, see the chapter application files for *simpleg_leon* scenario.

5 Discussion

There have been several attempts to project future water withdrawals based on gridded models (Herbert and Döll 2019), county-level analysis (Roy et al. 2012), Hydrologic Unit Codes (Brown et al. 2019), or at global scales (Boretti and Rosa 2019). However, most current studies have ignored the role of technological progress (measured here as TFP). We show that productivity improvements in crop production, the livestock sector, and processed food activities can offset the pressure on water resources over the coming decades. However, investments in research and development (R&D) are required to achieve the suggested productivity improvements (see Chap. 10 as well as Baldos et al. 2018; Baldos and Hertel 2018). Continued improvements in productivity—which have followed investments in R&D over the past—are essential to avoid increasing stress on water resources. Although improvements in irrigation efficiency are expected to increase water use (Perry et al. 2017; Grafton and Wheeler 2018; Perry 2019), growth in productivity can reduce the stress on water resources by offsetting demand pressures. Given the uncertainty in TFP calculations, future studies should explore the consequences of alternative R&D and TFP trajectories (Fuglie et al. 2022).

Over the last few decades, policy discussions around groundwater sustainability have evolved from a legal and economic definition of safe yield (i.e., the amount of water that can be withdrawn before it is no longer economically feasible) to a more socially and environmentally based definition of sustainability that can provide a long-term balance between withdrawals and impacts (Alley et al. 1999; Alley and Leake 2004). Even a withdrawal amount that is replenished each year can lead to a decrease in natural discharge and cause harm to ecosystems that rely on groundwater contributions; in many locations, the sustainable yield is substantially less than the natural recharge rate (Sophocleous 2000). The sustainability scenario undertaken here, therefore, provides a conservative estimate of the economic impacts of a sustainable groundwater policy. In some cases, restricting groundwater withdrawals to estimated annual rates of recharge allows for extraction far above sustainable yields.

Aeschbach-Hertig and Gleeson (2012) and Piemontese et al. (2020) call for a more comprehensive socioeconomic strategy and more attention to the significance of local population and equity in sustainability studies. This study contributes to the growing body of evidence on the importance of the global–local–global approach for sustainable agriculture (Hertel et al. 2019, 2023; Haqiqi et al. 2022; Ray et al. 2023). While global costs of sustainability might be small due to economic responses and reallocation of resources, the local benefits of sustainability and local costs of ignoring it are significant.

Gleeson et al. (2012) argue that groundwater sustainability is a values-driven process involving social, economic, and environmental factors that cannot be defined in terms of a given withdrawal target and that sustainability planning for groundwater must utilize a long time horizon (50–100 years); involve local, adaptive input; and utilize models capable of backcasting from desired outcomes to policy options that can support them. This work utilizes a publicly available, multiscale modeling tool (SIMPLE-G) that can be incorporated into regional community planning efforts to examine the socioeconomic impacts of various management strategies over long time horizons. However, we would argue that, in addition to a local, physically based analysis to inform policy options, given linkages to the global food system, community-level planning for groundwater sustainability options must also include a broader perspective, considering the role of global economic drivers.

Another benefit of the multiscale modeling framework is its ability to capture the interactions of different countries' policies and their local impacts. Disaggregating production in the United States while keeping other regions ungridded in the background permits us to consider the market responses of US trade partners, even as we explore US domestic policies in detail. These global market developments are potentially important when they are implemented by major trade partners and food-producing countries. One outstanding example is China, which has been aggressively pursuing national policies to achieve sustainable agricultural development during the past decade. The National Sustainable Agricultural Development Plan (2015–2030), released in 2015, continues to emphasize the contributions of agricultural science and technology (more than 60% to total output growth), cropland protection (no less than 120 million hectares of cropland), and efficient irrigation (capped national irrigation water use at 700 billion m^3 by 2030 and an irrigation efficiency index no lower than 0.60). It is important to be able to factor such major developments into the analysis of US agriculture and sustainability policies at the national and local levels.

This study shows that SIMPLE-G is a useful tool that can provide insights into the spatial distribution of solutions to environmental problems on cultivated land. This information can be used by policymakers to identify the areas most affected by environmental problems, allowing them to focus their efforts on resolving these problems in the most efficient way possible. It is also helpful when evaluating the effectiveness of environmental policies and understanding the unintended consequences that may arise. As shown in this chapter, as well as in other applications in this book, the SIMPLE-G framework can be used to assess the market-mediated impacts of environmental policies by analyzing the bidirectional feedback between distant locations through crop markets, labor markets, and fertilizer markets.

6 Conclusion

With limited technological progress, increasing stresses on water and land resources are projected to emerge because of anticipated growth in demand for food. Specifically, groundwater withdrawals in some locations are expected to increase by more than 50%. The underlying drivers of these stresses are global in nature, with demand growth in South Asia and China alone accounting for roughly one-quarter of US irrigated cropland expansion. However, strong productivity growth can offset the pressure from global changes in population and growth. Unfortunately, groundwater pumping for irrigation and other uses now exceeds annual recharge rates by more than 10 times in parts of the Central Valley of California, the High Plains Aquifer, and the Snake River Basin of the United States. This situation is expected to further deteriorate in the absence of regulation.

We find that local water policies can have unanticipated spillover effects, thereby exacerbating water stresses in other parts of the world. Furthermore, any attempt to restrict water for irrigation will result in the reallocation of cropping activity to other parts of the country and the world. Given the increase in water and land use in other parts of the world in the wake of the US sustainability policy (around 20 million hectares), the global net environmental benefit of such a policy may be limited or even negative due to spillover effects. Cropland expansion in other parts of the world can cause more biodiversity loss, deforestation, and water pollution. Addressing this sustainability challenge will require global coordination of resource governance as well as institutional reforms. The global–local–global framework here offers a practical means for analyzing the consequences of such policy proposals as they emerge.

The relationships among groundwater policy, land use, and its spillover effects reveal challenges and opportunities. SIMPLE-G has illuminated the pathways through which local water conservation resonates across borders, potentially amplifying environmental pressures elsewhere. The questions it provokes—about labor market dynamics, global food security, and the cascading impacts of sustainability strategies—remain central threads in the ongoing dialog about managing our precious, shared aquifer resources. Further research and policy evaluations are crucial for ensuring groundwater sustainability not just within localized contexts but also as a keystone for the health of our planet and its diverse inhabitants.

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