Chapter 11
Gridded Implications of Total Factor Productivity Growth

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This chapter introduces novel techniques for undertaking gridded analyses within the Simplified International Model of agricultural Prices, Land use, and the Environment (SIMPLE)-G framework. It builds on the baseline experiment developed in Chap. 10, which projected the global economy from 2017 to 2050 using the nongridded SIMPLE model. In this chapter, we replace the single, national production function in SIMPLE with a gridded representation of US agriculture, following the methodology laid out in Chaps. 3 and 5 and using SIMPLE-G1, a version of SIMPLE-G that does not distinguish between rainfed and irrigated agriculture. It also follows Chap. 10 in having only two inputs: land (natural resources) and nonland (human and produced) inputs. We begin by exploring the impacts of a marginal perturbation in US total factor productivity (TFP) growth, demonstrating that the model results mirror the results obtained by using the theoretical equations from Chap. 3. We then run the same global baseline scenario as in Chap. 10 and show that the equivalent gridded results can be obtained from a "minimodel," which takes as its inputs the US crop price change and exogenous grid-level shocks (in this case, TFP). This minimodel is highly amenable to in-depth analysis, one grid cell at a time. The chapter concludes by demonstrating how to attribute local grid-cell outcomes to global change drivers—including income, population, and technology—in non-US regions.

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

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I. Haqiqi, T. W. Hertel (eds.), *SIMPLE-G*,
https://doi.org/10.1007/978-3-031-68054-0_11

1 Introduction

In Chap. 10, which utilized the (nongridded) SIMPLE, the authors analyzed the impacts of environmental policies at a regional level (i.e., groups of countries). This approach allowed them to evaluate how national and regional investments in agricultural research and development (R&D) interact with environmental policies to achieve the dual goals of restricting harmful greenhouse gas emissions while minimizing adverse impacts on food affordability. The regional-scale SIMPLE model is well positioned for this analysis as it allows for complex regional interactions via food markets and spillover effects from technological advances. However, using SIMPLE at the regional level lacks the nuances of geographic specificity in the policy impacts that are determined by local-level biophysical and socioeconomic factors. For example, the conservation policies implemented in the previous chapter aim to conserve terrestrial carbon and biodiversity, yet these features of the landscape vary widely within each SIMPLE region. This calls for analysis at a more granular scale. This chapter employs the simplest possible version of the SIMPLE-G model developed in Part III, called SIMPLE-G1. Furthermore, we introduce the SIMPLE-G "minimodel" approach to gridded analysis—previously discussed in Chap. 3—which will allow us to focus on specific grids of interest to understand the determinants of individual grid-cell-level outcomes. This level of economic analysis has been missing from the integrated assessment models that are currently used to evaluate regional and global-scale environmental and conservation policies.

2 SIMPLE-G Version Employed

To highlight the benefits of the minimodel approach, we build on Chap. 10 and replicate the economic growth and TFP shocks from that chapter, using the gridded SIMPLE-G1 model. As a prelude to the next few chapters, we focus on the United States as the gridded region of interest. Our goal is to demonstrate how we can use the minimodel approach to delve into grid-cell-level results, relating these outcomes back to key economic and biophysical parameters.

As with the SIMPLE model utilized in the previous chapter, SIMPLE-G1 is based on two aggregated inputs: natural resources, a category that includes land and water inputs, and human resources, which includes all manufactured inputs and human labor. This two-input approach allows us to leverage the foundational economic theory laid out in Chap. 3 to understand the model results. After running the TFP shocks in the SIMPLE-G1-US model, we explain the model results and how they relate to the foundational theory, data, and parameters in the SIMPLE-G1 model. This deeper understanding of the SIMPLE-G1-US model provides the reader with a strong basis for exploring the more complex versions of the SIMPLE-G model featured in subsequent applications.

3 Experimental Design

Many factors can induce shifts in TFP, but one of the biggest contributors to changes in TFP is an investment in agricultural R&D. As in Chap. 10, R&D-induced TFP growth is assumed to uniformly affect the productivity of all inputs in all grid cells and is represented in this model by the variable p_AOCROP, which is the percentage change in a productivity index. With an increase in TFP ($p\_AOCROPr > 0$), the amount of each input required in region r to produce a given amount of output decreases. Therefore, to produce the same amount of food, producers need fewer human and resource inputs. However, if the region where TFP improvement occurs becomes more competitive, input use might increase due to an overall expansion in output level. In Chap. 2, we referred to this as Jevons' paradox and discussed the conditions under which this phenomenon will arise.

In this chapter, we consider three experiments. The first, which we use for illustrative purposes, simulates a 1% improvement in TFP in US grid cells. This marginal perturbation of the model allows us to use the analytical equations from Box 3.1 in Chap. 3 to explore in more depth the model theory, data, and parameters that drive the observed changes in both resource and human input use. In the second experiment, we implement the full set of population, income, TFP, and biofuel shocks, as implemented in the baseline R&D scenario in Chap. 10. Finally, we show how the exact same gridded outcomes can be obtained in a two-step simulation. In this case, we shock only the TFP in the US grid cells. However, we accompany this TFP shock with a market price shock that carries all the necessary information about global demands and supplies. We show that the US market price is a "sufficient statistic" embodying the boundary conditions facing any given grid cell in the United States. In other words, it is a complete summary of market developments elsewhere in the global economy. Once producers in a grid cell know this price, they do not need any other information to make informed economic decisions about production practices on their farms. We leverage this knowledge to facilitate grid-by-grid analysis of the results.

4 Selected Grids

For the minimodel analysis, we selected 12 grids to represent the range of important SIMPLE-G1 parameters (i.e., the land supply elasticity, cost share of land, and land–nonland input substitution elasticity). Table 11.1 lists the values of these parameters, and Fig. 11.1 shows the grid cells' location in the United States. In some grid cells—such as grid I04106 in the state of Washington (WA)—resource supply is largely unresponsive to price (i.e., it is inelastic); in others—such as grid I06314 in the state of Montana (MT)—resource supply is considerably more responsive to price. In contrast, the supply elasticity of human inputs is elastic and assigned a uniform value, given the lack of grid-cell-specific estimates of this parameter. The value of

Table 11.1 SIMPLE parameters for 12 selected grid cells for in-depth analysis of model results

Grid ID	Land supply elasticity	Nonland supply elasticity	Land cost share	Substitution elasticity
WA: I04106	0.003	1.340	0.2906	1.00
NV: I04259	0.003	1.340	0.1179	1.00
ID: I06003	0.102	1.340	0.2424	0.86
MT: I06314	0.255	1.340	0.0971	0.20
OK: I24220	0.111	1.340	0.1300	1.00
TX (1): I27726	0.326	1.340	0.1243	1.00
MN: I33495	0.004	1.340	0.2623	0.22
TX (2): I36312	0.350	1.340	0.2475	1.00
WV: I51326	0.368	1.340	0.2542	0.18
IN: I56025	0.129	1.340	0.2796	0.22
AL: I58595	0.144	1.340	0.1090	0.18
PA: I68537	0.300	1.340	0.0956	0.20

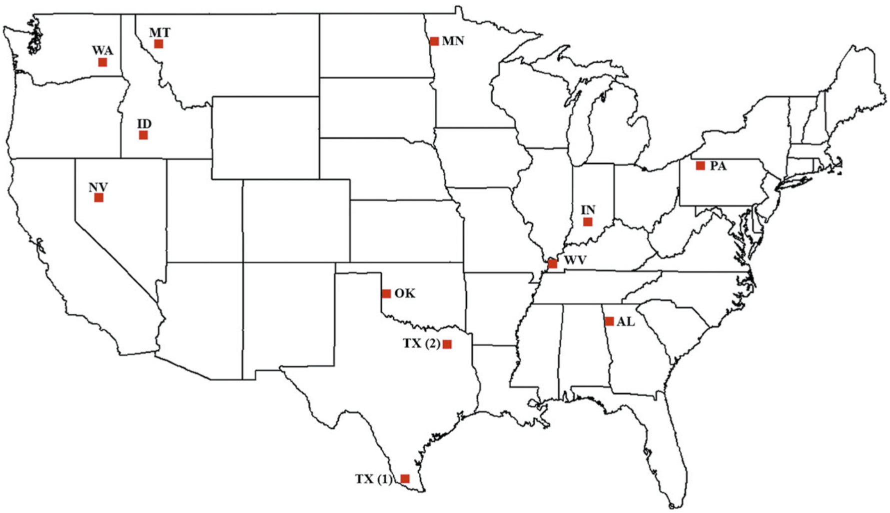

Fig. 11.1 Map of selected grid cells used in this chapter

the elasticity of substitution varies greatly across grid cells, implying that some grid cells have significant potential for boosting production at the intensive margin (i.e., substituting nonland for land inputs). For example, the elasticity of substitution is greater than 0.6 in Nevada (NV) and Idaho (ID) but much smaller in Indiana (IN) and Alabama (AL). A small value suggests that the application of more variable inputs (e.g., fertilizer) will not greatly increase yields. In Chap. 7, we discussed further details about how this parameter is calculated. Note also that the grid-cell-level share of land rents in total production costs is also quite variable, ranging between 10% and 30%. This will prove to be important in driving the results.

5 Results

For expository purposes, we begin with a simple 1% perturbation of TFP in the United States and examine how this plays out at the level of individual grid cells. This is a good opportunity to utilize the grid-cell-level theory developed in Chap. 3. We then analyze the impacts of the full baseline scenario from the preceding chapter. This approach allows us to explore the gridded impacts of this forward-looking baseline within the continental United States. Finally, we show how the minimodel can be used to replicate the results from the full model and explore them more deeply.

5.1 SIMPLE-G1 with a 1% TFP Shock in the United States

A 1% increase in TFP in the United States leads to a 1.3% increase in crop production with a 0.6% reduction in crop price. The improvement in TFP in the United States makes crops produced in the United States more competitive in the national and international markets and leads to an increase in overall production, which dominates the resource-conserving aspect of the TFP improvement. In contrast, the TFP boost in the United States is resource-conserving in the rest of the world (ROW): Production declines by 0.01–0.22% in the other 16 SIMPLE regions.

We present the results of the 1% US TFP shock for the 12 focus grids in the United States in Table 11.2. Columns 2–4 show the impacts of the 1% TFP shock on input use and crop production. Columns 5–7 show the same results calculated using the theoretical equations developed in Box 3.1. (We have omitted the calculations of input price changes, which can be explored using Eqs. 3.7 and 3.8.) By comparing these two sets of columns in Table 11.2, we show that the simulation model results can be replicated (for a marginal perturbation of the model) with our analytical model using the relevant parameter values. Note that, for larger (nonmarginal) changes, the analytical formulae may yield different results as these formulae are based on a local linearization of the underlying nonlinear model.

In the following, we reproduce the relevant equations from the foundational two-input analytical model presented in Box 3.1 to calculate the impacts of a 1% TFP change in the system. Recall that the change in TFP is captured with the a parameter, which refers to factor-neutral technical change in the production function. As the US crop price is also changing, we need to include the change in p as well. However, we omit the conservation policy shock ($\phi_R = 0$) that was the focus of discussion in Chap. 3.

Percentage change in input H use when $\phi_R = 0$:

Table 11.2 Simulated and calculated impacts of a 1% TFP shock to 12 selected grids in SIMPLE-G1

	Simulated results for 1% $AOCROP_g$ shock			Calculated results for $a = 1$ using Eqs. 11.1, 11.2, and 11.5		
Grid ID	Nonland input	Land input	Output	Nonland input (Eq. 11.1)	Land input (Eq. 11.2)	Output (Eq. 11.5)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
WA: I04106	0.37	0.002	1.27	0.38	0.002	1.27
NV: I04259	0.45	0.002	1.4	0.45	0.002	1.40
ID: I06003	0.40	0.069	1.32	0.40	0.069	1.32
MT: I06314	0.31	0.004	1.29	0.42	0.002	1.41
OK: I24220	0.45	0.079	1.41	0.46	0.080	1.41
TX (1): I27726	0.47	0.203	1.44	0.48	0.205	1.44
MN: I33495	0.20	0.004	1.15	0.20	0.004	1.15
TX (2): I36312	0.44	0.199	1.38	0.44	0.200	1.38
WV: I51326	0.36	0.272	1.34	0.36	0.274	1.34
IN: I56025	0.26	0.113	1.22	0.27	0.114	1.22
AL: I58595	0.37	0.186	1.35	0.37	0.188	1.35
PA: I68537	0.43	0.298	1.42	0.44	0.301	1.42

$$q_H = v_R \frac{(p^* + a)}{\theta_R} \Gamma_H + \sigma \frac{(p^* + a)}{\theta_R} \Gamma_H; \tag{11.1}$$

Percentage change in input R use when $\phi_R = 0$:

$$q_R = (p^* + a) \frac{v_R}{\theta_R} \Gamma_R; \tag{11.2}$$

Percentage change in price of input H when $\phi_R = 0$:

$$p_H = \frac{p^* + a}{\theta_H} (1 - \Gamma_R); \tag{11.3}$$

Percentage change in price of input R when $\phi_R = 0$:

$$p_R = \frac{p^* + a}{\theta_R} \Gamma_R; \tag{11.4}$$

Percentage change in production when $\phi_R = 0$:

Table 11.3 Decomposition of total change in crop production as a percentage change

Grid ID	Total change in crop production Result of Eq. 11.5.	Direct impact of TFP increase First element of Eq. 11.5	Extensive margin response to price change Second element of Eq. 11.5	Intensive margin response to price change Third element of Eq. 11.5
(1)	(2)	(3)	(4)	(5)
WA: I04106	1.27	1	0.002	0.266
NV: I04259	1.40	1	0.002	0.396
ID: I06003	1.32	1	0.069	0.249
MT: I06314	1.14	1	0.002	0.136
OK: I24220	1.41	1	0.080	0.328
TX (1): I27726	1.44	1	0.205	0.238
MN: I33495	1.15	1	0.004	0.147
TX (2): I36312	1.38	1	0.200	0.182
WV: I51326	1.34	1	0.274	0.064
IN: I56025	1.22	1	0.114	0.109
AL: I58595	1.35	1	0.188	0.165
PA: I68537	1.42	1	0.301	0.122

$$q = a + (p^* + a)\frac{v_R}{\theta_R}\Gamma_R + (p^* + a)\frac{\sigma\theta_H}{\theta_R}\Gamma_\sigma, \tag{11.5}$$

where $\Gamma_H = \frac{\theta_R v_H}{\text{denom}}$, $\Gamma_\phi = \frac{\theta_R(v_H+\sigma)+\theta_H\sigma}{\text{denom}}$, $\Gamma_\sigma = \frac{\theta_R(v_H - v_R)}{\text{denom}}$, and $\text{denom} = \sum_{j,k}\theta_j(v_k + \sigma), j, k = H, R$ for $v_R < v_H$.

It is clear from Eqs. 11.1, 11.2, 11.3, 11.4, and 11.5 and the results in Table 11.3 that SIMPLE-G results are firmly underpinned by economic theory. This is important, as it allows for a thorough explanation of the model results, and the results can be related back to key parameters. In addition, the theory allows us to decompose the simulation results to understand the biophysical and socioeconomic grid-cell characteristics that drive those results. For example, using Eq. 11.5, we can explore the elements that contribute to the total change in crop production due to a change in TFP. Table 11.3 decomposes the total change in crop production into the direct impact of a 1% increase in TFP (first element of Eq. 11.5) and the supply response to the ensuing price change, which comprises both an extensive margin (second element of Eq. 11.5) and an intensive margin (third element of Eq. 11.5) of the supply response. Column 4 of Table 11.4 shows that the extensive margin response

Table 11.4 Minimodel analysis of grid-cell impacts of the baseline scenario, incorporating population, income, biofuels, and technology growth worldwide, 2017–2050

Grid cells	Baseline	Minimodel		
		Total	Market price	Own-TFP
(1)	(2)	(3)	(4)	(5)
Panel A. Cropland change by grid cell (QLAND)				
WA: I04106	0.08	0.08	−0.08	0.17
NV: I04259	0.10	0.10	−0.10	0.20
ID: I06003	2.98	2.99	−2.91	5.90
MT: I06314	0.14	0.14	−0.13	0.27
OK: I24220	3.45	3.45	−3.36	6.81
TX (1): I27726	9.10	9.10	−8.92	18.02
MN: I33495	0.17	0.17	−0.16	0.33
TX (2): I36312	8.88	8.89	−8.71	17.59
WV: I51326	12.12	12.12	−11.87	23.99
IN: I56025	4.77	4.78	−4.64	9.41
AL: I58595	7.92	7.92	−7.70	15.62
PA: I68537	13.37	13.37	−13.11	26.48
Panel B. Crop output by grid cell (QCROP)				
WA: I04106	55.42	55.43	−14.24	69.66
NV: I04259	64.31	64.32	−21.94	86.26
ID: I06003	58.72	58.73	−17.07	75.80
MT: I06314	54.57	54.57	−13.15	67.72
OK: I24220	64.95	64.96	−22.50	87.46
TX (1): I27726	67.46	67.47	−24.69	92.16
MN: I33495	47.00	47.00	−6.87	53.87
TX (2): I36312	63.18	63.19	−20.95	84.14
WV: I51326	59.63	59.63	−17.78	77.41
IN: I56025	51.72	51.72	−10.93	62.65
AL: I58595	59.80	59.81	−17.80	77.61
PA: I68537	65.39	65.40	−22.77	88.17

These impacts are conveyed to grid cells via the US market price for crops combined with the local change in technology. This approach allows for accurate prediction of local impacts as derived from the full model

to the price change closely follows the magnitude of the price elasticity of resource supply reported in Table 11.1. In grids like that in Washington, where the supply elasticity is very small (0.003), the extensive margin response is also negligible (0.002). However, in West Virginia, the supply elasticity of resources is 0.37, leading to the largest extensive margin supply response in this table (0.27). Similarly, in grids where the substitution elasticity between the two inputs is large (e.g., 1), such as in Nevada, the intensive margin supply response is much larger. In Nevada, this parameter reaches its largest value in this table: 0.396.

5.2 *SIMPLE-G1 with a Complete Baseline*

In this section, we repeat the baseline experiment from Chap. 10, shocking not only the supply side (i.e., TFP in the United States and TFP in other world regions) but also the demand side, including population, income, and changes in demand for biofuels for 2017–2050. This experiment generates regional outcomes similar to those in Chap. 10, but it also allows us to explore the impacts of demand and supply side shocks in the ROW on individual grid cells across the United States. The United States is a major producer of food consumed across the world. This implies that both changes in the productivity of the agricultural sector and changes in food demand in the ROW have a substantial impact on the US agricultural sector. To better investigate this phenomenon, we replicate the set of shocks from Chap. 10 using the SIMPLE-G1 model while utilizing the subtotal feature of GEMPACK to further decompose the impacts of those shocks into ten groups of drivers:

1. Change in population in ROW.
2. Change in income in ROW.
3. Change in biofuel demand in ROW.
4. Change in crop TFP in ROW.
5. Change in TFP in the crop-using sectors (livestock and processed foods) in ROW.
6. Change in population in the United States.
7. Change in income in the United States.
8. Change in biofuel demand in the United States.
9. Change in crop TFP in the United States.
10. Change in TFP in the Crop-Using Sectors (Livestock and Processed Foods) in the United States

We further show that all the information about these developments across the global economy is conveyed to US producers locally through changes in crop prices. Therefore, changes in grid-cell-level production can be replicated by simply implementing a US crop price shock along with any local-level TFP changes affecting individual producers.

5.2.1 Impact of Baseline Scenario on US Crop Price

Under this baseline scenario for 2017–2050, growth in global supplies outpaces growth in global demands, and the crop price declines globally and in the United States where it falls by 14.90%. However, TFP grows—hence unit costs fall. The cost decrease is greater than the fall in prices, so there are benefits to be gained at the farm level. A large share of these gains is captured by the inelastically supplied natural resource input, the rents of which increase by 55.44%. However, returns to human and manufactured inputs (the more elastically supplied input) increase by a relatively smaller amount, 9.87%.

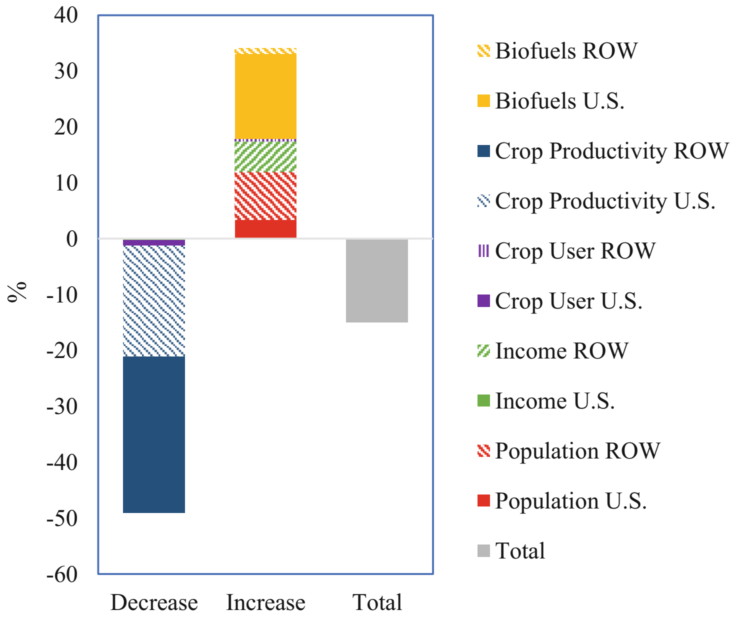

Fig. 11.2 Decomposition of changes in US crop price by ten sources of change, 2017–2050

Figure 11.2 utilizes the subtotal feature of GEMPACK to decompose the total change in US food prices into the ten sources of global change drivers identified above. The main factor that leads to the reduction in crop prices in the United States is the technological improvements in crop productivity due to agricultural R&D investments in the United States and the ROW. Improved productivity in crop-using sectors (i.e., livestock and processed foods) also generates a small amount of downward pressure on prices. Increases in global population and income lead to increased demand and therefore put upward pressure on crop prices. Demand for crops from the US biofuel sector is also a major contributor to upward pressures on US crop prices.

5.3 SIMPLE-G1-Mini

The SIMPLE-G1-Mini model is designed to replicate individual grid-level results produced by a SIMPLE-G1 model considering only the equilibrium price changes from SIMPLE-G1. This is possible because the price changes carry all the relevant market information determined by the global model. The SIMPLE-G1-Mini model can be run on a few selected grids (e.g., the 12 grids discussed above). These grid cells are typically selected due to their (perhaps surprising) outcomes as well as their potential relevance to local policymakers. Of course, any local policy or technology changes must also be communicated to the gridded model. Therefore, in the case of this SIMPLE-G1 experiment, each grid cell will be shocked by both the crop price (which is deemed exogenous to local producers) and the TFP improvement experienced by local producers.

Column 2 in Table 11.4 (baseline) reports the gridded impacts from the baseline scenario, run with the full set of shocks to population, income, biofuels, and technology around the world in a model with thousands of grid cells. Columns 3–5 report the results from the minimodel, which is run for individual grid cells by shocking the market price as well as grid-cell-level technology (own-TFP). Note that the total impact agrees with the baseline results to the first decimal point. We have successfully transferred global supply and demand information to the grid cells via the crop price signal. The impact of this change in market conditions is reported in column 4. If producers in the WA grid cell do not experience a TFP improvement over the 2017–2050 time horizon, they will reduce cropland (QLAND = − 0.08) and output (QCROP = − 14.24). However, this model assumes that producers experience the average rate of TFP growth in the entire US region. As a consequence, their costs fall, and they end up expanding cropland cover as well as output. The remaining entries in this table report the market price and own-TFP impacts on cropland and output for the other 11 grid cells illustrated in Fig. 11.1. Note that the responses vary widely due to the widely varying grid-cell-level parameter values reported in Table 11.1.

We see that the grid cell labeled TX (1) has the largest increase in crop production, 67.46%, driven by the relatively high supply elasticity of land (0.326) and substitution elasticity (1) as shown by the parameters in Table 11.1. Both of these factors ensure that the producers in the grid cell can respond to the TFP shock with more flexibility. On the contrary, the grid cell labeled MN has a combination of parameters (small land supply elasticity and small elasticity of substitution between human and natural resource inputs) that limits producers' ability to respond to the TFP shock; it therefore reports the smallest increase in crop production.

The grid cell labeled PA shows the largest increase in cropland area, the result of a large increase in the price of land. The magnitude of this price increase is inversely proportional to the cost share of land (recall Eq. 11.4). The reason is that as unit costs fall due to the TFP shock, the associated benefits that are not passed forward to consumers in lower prices are passed backward to input suppliers, with the relatively inelastic input (land, in this case) garnering more of the gains. As the land resources currently account for only a small share of total costs (less than 10% in the case of the PA grid cell), the resulting increase in percentage returns must be very large. This increase in land returns operates on the land supply elasticity, which is also relatively large (0.3, see Table 11.1), resulting in an increase of more than 13% in cropland area. In short, each grid cell has its own story, even though they all face the same changes in national price and TFP. Their outcomes are varied, reflecting the interplay of cost shares, factor supply elasticities, and input substitution possibilities as seen in Eqs. 11.1, 11.2, 11.3, 11.4, and 11.5.

5.4 A Global-Local-Global Analysis for Selected Grid Cells

With this minimodel in hand, we can also quantify the impact of diverse global change drivers on local outcomes in individual grid cells. Figure 11.3 illustrates this global-to-local linkage in the case of crop output growth in the WA grid cell. Table 11.4 reports the growth in output (Grid Total) in the WA grid cell as 55.4%. How much of this is due to economic developments in the non-US, ROW regions? By combining the results in Fig. 11.2 with those in Table 11.4, we can calculate a full attribution of local output changes to the underlying global drivers. Figure 11.3 reports these results. Crop productivity growth—both in the United States and in the ROW—depresses prices and discourages output in the WA grid cell. However, biofuel production, income, and population growth boost prices and hence output. The net impact of these market price effects on crop output is negative (Table 11.4). However, when combined with the own-TFP impacts, which lower producer costs, output in the WA grid cell is predicted to rise.

These findings are obtained by combining results from Fig. 11.2 with those from Table 11.4.

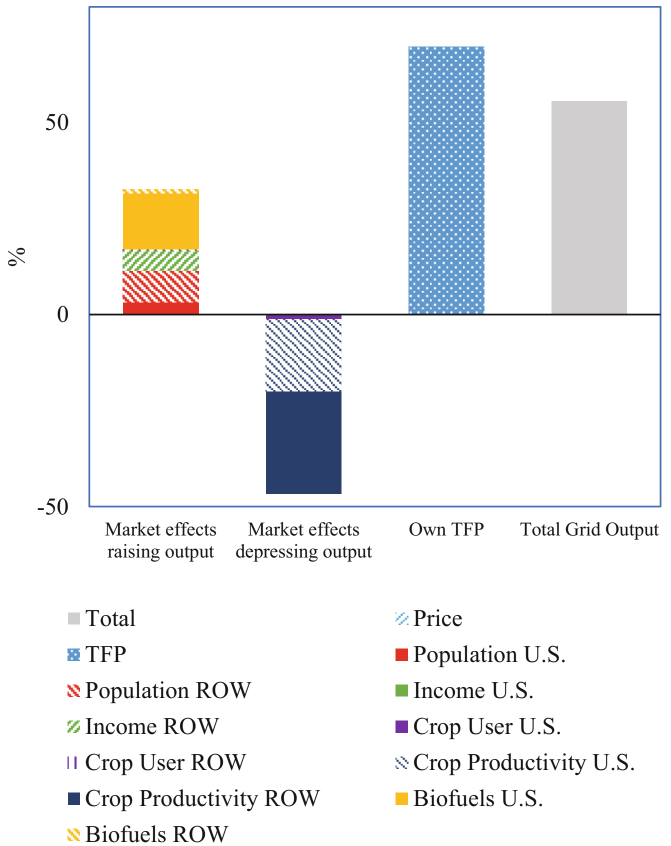

Fig. 11.3 Decomposing the global and local drivers of crop output in grid WA

6 Conclusions

This chapter is key for those who wish to evaluate the critical drivers and processes in sustainability analyses using SIMPLE-G. The SIMPLE-G1 and minimodel are useful tools when a deeper analysis is required to understand—and explain—spatially heterogeneous results. As has been shown here, to understand what is behind a given set of results, it is essential to refer back to the underlying parameters and explore the connection to regional and global markets.

The tools introduced in this chapter are also helpful for uncertainty analyses and robustness checks. It is worthwhile to conduct a systematic sensitivity analysis of model results with respect to the uncertainty in the underlying parameters and drivers. Building meaningful confidence intervals around the results is an important part of the scientific endeavor.

The beauty of these SIMPLE-G tools is that they allow researchers to improve transparency and traceability of global economic analysis of food security and environmental sustainability while also drawing out the implications of these global developments for local outcomes. Exploring the links among global drivers, local stresses and responses, and feedback at the global level is a central theme of this book.

Acknowledgments and Competing Interests The authors acknowledge support from the National Science Foundation, including INFEWS award #1855937, "Identifying Sustainability Solutions through Global-Local-Global Analysis of a Coupled Water-Agriculture-Bioenergy System" and AccelNet Award #NSF-OISE-2020635, GLASSNET, from the US Department of Agriculture NIFA grants #2019–67,023-29,679, "Economic Foundations of Long Run Agricultural Sustainability," and 2022–67,023-36,403, "Labor Markets and the Impacts of Environmental Stresses and Conservation Policies on US Agriculture," as well as USDA Hatch Project 1,003,642.

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