Chapter 3
Grid-Level Analysis Using SIMPLE-G

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While it is instructive to engage in aggregate market analysis of the sort discussed above, in the end, most sustainability issues are local in nature and depend on local biophysical conditions (e.g., climate, soils, hydrology, and land cover) and socio-economic circumstances (e.g., local governance, household characteristics, and choice of technology). To incorporate these sources of heterogeneity into a global sustainability analysis, a finer spatial resolution is necessary. Typically, physical scientists characterize fine scales using grid cells, which are spatial units of equal length and width, with the area varying according to the latitude of the grid cell (larger at the equator and smaller moving toward the poles). The resolution of grid cells in SIMPLE-G and the construction of the underlying data are the subject of Part III of this book. At this point, it is sufficient to note that the grid cells in SIMPLE-G are small enough to allow the incorporation of available heterogeneity in data and parameters and small enough to not influence commodity prices, so they can be treated exogenously. In the SIMPLE-G-US model, for example, approximately 75,000 grid cells are involved in US crop production.

Taking global and national drivers of market outcomes as exogenously given allows us to focus on relationships within the grid cell. This approach greatly simplifies our gridded analysis and allows us to reach some important conclusions about the likely impact of a global change in commodity prices on local land and

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water use as well as labor demand. Of course, since every grid cell will likely respond to any global changes and may compete for common inputs (e.g., labor and fertilizer), we cannot understand the full impact of these market developments without considering all grid cells simultaneously. Since the combined responses of all the grid cells influence global supply and hence world prices, this model must ultimately be solved as a multiscale system. This will be discussed at length in Part III.

The specific design of the crop production functions in SIMPLE-G is also discussed at length in Part III. In general, design will vary by application. *SIMPLE-G is a framework*, not a single model. In this section, we illustrate the framework with a two-input specification. In the two-input case, we continue to group the natural resource-related inputs (e.g., land) into one aggregate, which will be termed "resources" and indexed with *R*. Resources include all inputs required for agricultural production that are sourced from nature, including cropland, groundwater, and surface water. In practice, we also include irrigation equipment in the resources category since it refers to investments needed to augment natural inputs and make them suitable for crop production. In the two-input case, the second aggregate of production factors encompasses all remaining inputs, including human labor and manufactured inputs (e.g., seeds, chemicals and fertilizers, and capital), and is indexed with *H*. As we will see, the economic distinction between these two input categories rests upon the underlying factor supply elasticities (i.e., how responsive these input supplies are to price changes). Given the geographic immobility of resources, we generally expect the factor supply elasticity for resource inputs to be lower than that for human and manufactured inputs, which we expect to be mobile across geographic locations.

Box 3.1 outlines the basic two-input, gridded model (Ray and Hertel 2023). The model uses a two-input CES production function, which allows for factor-neutral technical changes.[1] Since we are interested in studying changes in input use, input prices, and crop production as a result of an exogenous shock, Equations. 3.1–3.9 in Box 3.1 are presented in terms of percentage change in the corresponding variable. Equations 3.1–3.3 form the crux of the analytical framework for the two-input model. Equation 3.1, i.e., the conditional demand for either input, is derived from the usual producers' cost minimization problem (Gohin and Hertel 2003). Equation 3.2 is the constant price elasticity input supply equation for either inputs. It also includes a policy lever. For example, in case of resources, a positive value for the policy lever implies a backward shift in resource supply that can be implemented to model conservation policies that restrict the availability of resources. Equation 3.3 represents the zero-profit equation that enforces the free entry and exit assumption in

[1] The factor-neutral technical change parameter is useful in studying the impacts of improvements in total factor productivity on input use, input price, and total production. This is studied in depth in Chaps. 10 and 11.

the agricultural sector that ensures a competitive market structure, where any changes in crop price are attributed to both inputs in inverse proportion of their cost share.

Box 3.1: A Partial Equilibrium Two-Input Theoretical Model for Agricultural Production: Assessing the Impact of Conservation Policies

Agricultural production (Q) is a constant elasticity of substitution (CES) function of two inputs, natural resources (Q_R) and manufactured or human inputs (Q_H), augmented by any changes in total factor productivity (a), in a relevant spatial unit.

Percentage change in conditional demand of input j:

$$q_j^D = (q - a) - \sigma\{p_j - (p + a)\} \text{ for } j = R \text{ or } H \tag{3.1}$$

Percentage change in supply of input j with supply shifters:

$$q_j^S = v_j p_j - \phi_j \tag{3.2}$$

Zero-profit condition in terms of percentage change:

$$p + a = \sum_{j=R,H} \theta_j p_j, \text{ where } \sum_{j=R,H} \theta_j = 1 \tag{3.3}$$

Percentage change in optimized agricultural supply:

$$q^S - a = (p + a)\varepsilon - \Gamma_R \phi_R, \tag{3.4}$$

where $\varepsilon = \left[\frac{1}{\frac{\theta_R}{v_R+\sigma} + \frac{\theta_H}{v_H+\sigma}} - \sigma\right]$, $\Gamma_R = \frac{\theta_R(v_H+\sigma)}{\text{denom}}$ and $\text{denom} = \sum_{j,k} \theta_j (v_k + \sigma), j, k = R, H.$

Using Eqs. 3.1–3.4, the equilibrium changes in input use and output for a given $p = p^*$ follow:

Percentage change in input H use (Q_H):

$$q_H = v_R \frac{(p^* + a)}{\theta_R} \Gamma_H + \sigma \frac{(p^* + a)}{\theta_R} \Gamma_H - \phi_R \Gamma_H. \tag{3.5}$$

Percentage change in input R use (Q_R):

$$q_R = (p^* + a) \frac{v_R}{\theta_R} \Gamma_R - \phi_R \Gamma_\phi. \tag{3.6}$$

(continued)

Box 3.1 (continued)

Percentage change in price of input H (P_H):

$$p_H = \frac{p^* + a}{\theta_H}(1 - \Gamma_R) - \frac{\theta_R \phi_R}{\text{denom}}. \tag{3.7}$$

Percentage change in price of input R (P_R):

$$p_R = \frac{p^* + a}{\theta_R}\Gamma_R + \frac{\theta_H \phi_R}{\text{denom}}. \tag{3.8}$$

Percentage change in production (Q):

$$q = a + (p^* + a)\frac{v_R}{\theta_R}\Gamma_R + (p^* + a)\frac{\sigma\theta_H}{\theta_R}\Gamma_\sigma - \phi_R\Gamma_R, \tag{3.9}$$

where $\Gamma_H = \frac{\theta_R v_H}{\text{denom}}$, $\Gamma_\phi = \frac{\theta_R(v_H+\sigma)+\theta_H\sigma}{\text{denom}}$, $\Gamma_\sigma = \frac{\theta_R(v_H - v_R)}{\text{denom}}$ for $v_R < v_H$, $0 < \Gamma_\sigma < \Gamma_H < \Gamma_R < 1$.

Notation: All price and quantity variables are denoted with lowercase representing percentage changes in the underlying indices.
$\sigma \geq 0$: Elasticity of substitution between two inputs.
$v_j \geq 0$, $\theta_j \geq 0$: Elasticity of supply to agriculture and cost share of input j.
$\phi_H = 0$, $\phi_R > 0$: Backward supply shifter for input R due to, for example, a conservation policy
Source: Ray and Hertel (2023).

Setting input demand equal to supply to clear the input markets (i.e., Eq. 3.1 = Eq. 3.2) and using Eq. 3.3, we arrive at Eq. 3.4, which is the change in optimized output supply (Ray and Hertel 2023). Changes in output supply could be due to changes in crop price, depending on the output supply elasticity (ε) and any policy shock that restricts the availability of resources. The supply elasticity is itself a function of the input supply response, cost shares, and input substitution parameters and therefore is endogenous to the model. The degree of responsiveness of changes in production to changes in output price depends on the fundamental parameters of the input markets and production function. Finally, Eqs. 3.5–3.8 show the changes in use and price of both inputs, and Eq. 3.9 gives the change in crop production.

Despite all the simplifying assumptions (i.e., a single composite crop, exogenous crop price, only two inputs), we see that the impact of a change in crop price (p) or a conservation policy, modeled as a backward shift in the resource supply curve (ϕ_R), can nonetheless be rather complex. Fortunately, we can manipulate and interpret these expressions to generate valuable insights using more complex versions of SIMPLE-G, developed in Part III and applied in Part IV of this book. In the remainder of this section, we discuss the impacts of an exogenous crop price change and a conservation policy shock on resource and augmented human input use, input prices, and crop production within this relatively simple production structure.

1 The Case of Perfectly Elastic Human and Manufactured Input Supplies

To begin with, we make the simplifying assumption that labor and manufactured inputs are available with perfectly elastic supply to producers in the grid cell.[2] The actual supply elasticity of manufactured inputs is likely to be high in the medium run since inputs such as seeds, fertilizer, and chemicals can be transported relatively easily over long distances. While the assumption of perfectly elastic supply is clearly an oversimplification in the case of agricultural labor, this assumption is commonly used to simplify analyses. To highlight the importance of explicit modelling of agricultural labor markets, we begin with this assumption and then contrast our findings with the case of inelastically supplied labor. The perfectly elastic supply of human inputs implies that additional workers, if required, can be hired at the current wage rate. It also implies that workers can move long distances in search of work at the going wage rate.

Taking the output price and wages as exogenous, we can solve for the grid cell output response under the perfect mobility scenario, obtaining Eq. 3.9 (see Box 3.1). Note that the scaling terms, Γ_R and Γ_σ, are all equal to 1 in the special case of perfectly elastic human and manufactured input supply. The first term on the righthand side of Eq. 3.9 reflects the impact of an increase in Total Factor Productivity (TFP) in the grid cell. Holding all else constant, a 10% increase in TFP generates a 10% increase in output. The second term on the righthand side of Eq. 3.9 refers to the extensive margin of supply response in the face of an output price change. A rise in output price encourages producers to bring more resources into crop production. The responsiveness of resource use to an output price change depends on the percentage change in land rents, $\left[\frac{p^*+a}{\theta_R}\right]$, as well as the resource supply elasticity, ν_R. The fact that the crop price is “magnified” as it is translated into resource rents, $\left[\frac{1}{\theta_R} > 1\right]$, stems from the fact that wages do not change. This means that the increase in revenue is entirely capitalized into resource values. We expect both the cost share of resources and the resource supply elasticity to vary greatly by location, determined by both biophysical and socioeconomic factors. For example, in farmland areas adjacent to suburban and urban centers, we expect the cost share of resources to be high and the resource supply elasticity to be low, driven by the high

[2] Box 3.1 shows the analytical results when both inputs are inelastically supplied. The reader can derive the results when human inputs are perfectly elastically supplied by considering Eqs. 3.5–3.9 under the assumption that $\nu_H \to \infty$. When $\nu_H \to \infty$, each of the gamma terms tends to 1.

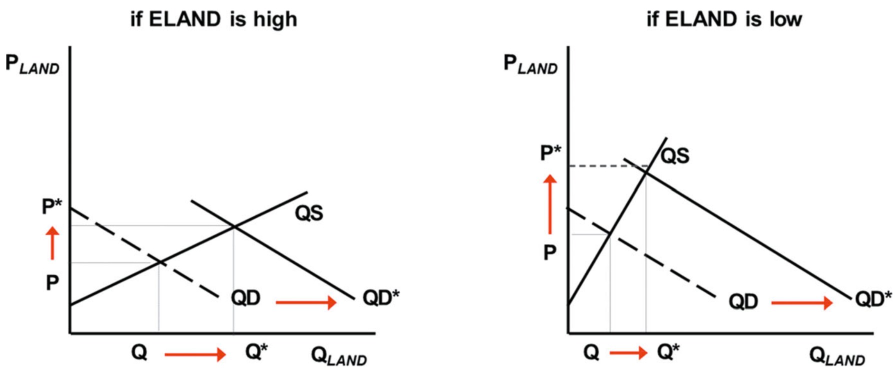

Fig. 3.1 Cropland area response under varying land supply conditions

rental value of land and relatively lesser availability of previously uncultivated land that can be brought under production in such areas. When combined, these factors result in a small extensive margin of supply in areas adjacent to urban centers. The opposite will be true in more remote locations where competition for land is more limited.

Figure 3.1 illustrates the differential responses of these two land supply situations in the face of increased crop demand. In the case of a remote location with a high land supply elasticity, an outward shift in demand translates mostly into cropland expansion, with only a minor impact on land returns. However, in regions where the land supply response is highly constrained, an outward shift in demand is primarily reflected in higher land prices.

The third term in Eq. 3.9 refers to the intensive margin of supply response to the output price change, $(p^* + a)\frac{\sigma\theta_H}{\theta_R}$. Once again, the magnification effect, $\left[\frac{1}{\theta_R} > 1\right]$, plays a role, as it translates the change in commodity prices into land prices. When human inputs are dominant, such that θ_H is large and θ_R is small, then this intensification effect will be more pronounced.

The elasticity of substitution between natural and human inputs, σ, also plays a key role in the intensive margin of supply in this model. A larger substitution elasticity indicates more potential for increasing crop yields in the face of heightened resource scarcity. Figure 3.2 illustrates the role of input substitutability in this framework in the context of a decline in human input prices facing producers in a given grid cell. When it is possible to vary the input mix (panel A), farmers' response to this price decline is to increase human inputs per hectare of land. The extent to which such substitution occurs—and hence the yield response to the price shock—depends on the curvature of the isoquant in panel A. The closer the isoquant is to a straight line, the higher the elasticity of substitution between resource and human inputs and the greater the impact on crop yields. Panel B illustrates the case where it is not possible to substitute human inputs for resource inputs; thus, yields do not change and resource and human inputs continue to be used in the same proportion.

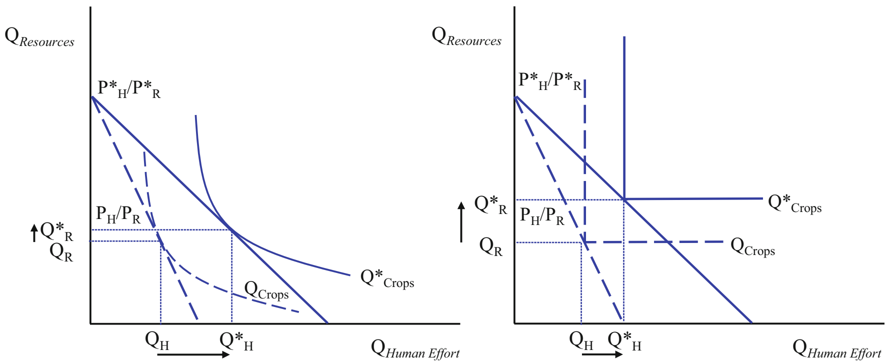

Fig. 3.2 Input substitution determines the magnitude of the intensive margin of supply

Of course, input usage still rises, as farming has become more profitable in the case of the human input price decline.

The final term in Eq. 3.9 relates to the effect of a conservation policy in which land is set aside, $\phi_R > 0$, to make room for nature and the delivery of other ecosystem services. In the absence of any impact on price, resource rents cannot change; with wages exogenously given (i.e., $\Gamma_R \rightarrow 1$), this translates into an equiproportionate decline in output. In reality, prices and resource rents will be affected, which will have consequences for potential "policy slippage," rendering the conservation policy less effective than initially expected for due to market-mediated responses by the affected producers.

The direction of change in human (Eq. 3.5) and resource (Eq. 3.6) input use depends on the total (extensive + intensive) supply response to the output price change (first term) net of the conservation policy shock (second term). If the conservation policy shock is dominant, $\left[(p^* + a)\frac{\nu_R+\sigma}{\theta_R} < \phi_R\right]$, then the total supply response only partially offsets job losses due to the conservation policy shock leading to a fall in employment and resource use. In contrast, if the total supply response is dominant, $\left[(p^* + a)\frac{\nu_R+\sigma}{\theta_R} > \phi_R\right]$, then there is an increase in employment and resource use in the grid (Ray and Hertel 2023). While wages remain constant by assumption in this first case, resource rental values increase unambiguously since scarcity in resources drives up their price.

2 The Case of Inelastically Supplied Human and Manufactured Inputs

When human inputs are also in less than perfectly elastic supply, the impacts of a commodity price increase and/or a conservation policy can be quite different from those of the preceding case. Here there is a possibility that workers might suffer a decline in wages, for example, in the context of a conservation policy. It also means that the magnification effect that boosted land rents so strongly in the context of a commodity price hike will no longer be so pronounced. In general, all the grid cell responses—extensive and intensive responses to output prices and the consequences of a conservation policy—are now more muted. This may be seen from Box 3.1 by the fact that the multiplicative scaling factors in Eqs. 3.1–3.5 (i.e., Γ_R, Γ_H, Γ_σ, and Γ_ϕ) lie between 0 and 1 as long as the resource input has the smaller supply response—an assertion that draws intuition from the fact that land is geographically immobile.

Under relatively inelastic labor market conditions, the factor supply elasticity determines the degree to which the production response to the conservation policy is dampened. This is because in a relatively tight labor market, it is more expensive to hire workers to manage the resources under production. Therefore, there is a smaller increase in resource use and employment when labor is inelastically supplied.

Further examination of the scaling terms reveals the role that labor supply elasticity plays in governing local responses to a commodity price boom (or bust). The difference in factor supply elasticities is clearly critical: If they are equal in value, then $\Gamma_\sigma = 0$, and there will be no incentive to intensify production in response to the commodity price hike. The rationale is that if both labor and the natural resource input are equally responsive to their respective factor prices, then these prices will respond symmetrically to the commodity price shock, increasing at the same rate. Since there is no incentive to substitute labor for resources, input use will also rise in lockstep with change in production.

Finally, if we consider the impact of a conservation policy on grid cell production, employment, and land use, we see that (holding output prices fixed) a policy reaches its maximum impact when labor is perfectly mobile since the conservation policy shock is premultiplied by the scaling factors. This is because the scaling factors reach their maximum value of 1 when labor is perfectly mobile. Therefore, as labor becomes less mobile, we expect that the impacts of a conservation policy, implemented as a shift in land supply, will become less effective.

3 Summary

The gridded theory provides a framework for understanding the complex relationships between market outcomes, land and water use, and labor demand at a local level. Given national drivers, the theory allows us to focus on relationships within individual grid cells. The two-input, gridded model uses a two-input production function, allowing for factor-neutral technical change. The economic distinction between the two input categories (resources and human/manufactured inputs) rests upon their availability to the agricultural sector, as captured by the underlying economic supply elasticities. These theoretical results highlight the fact that the impact of a change in crop price or a conservation policy can be complex, and a firm grasp of the underlying parameters is required to assess these impacts. This is as far as economic theory can take us. To say more about the potential impacts of a conservation policy, we need a quantitative model that can be parameterized and simulated in the face of a specific policy. Part III outlines the SIMPLE-G modeling framework as it is implemented numerically on a computer in order to assess the impacts of specific policies in specific contexts.

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