NBER WORKING PAPER SERIES

MEASURING CLIMATE CHANGE IMPACTS ON AGRICULTURE: AN EQUILIBRIUM PERSPECTIVE ON SUPPLY-SIDE APPROACHES

Christophe Gouel

Working Paper 30279
http://www.nber.org/papers/w30279

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
July 2022

I am grateful to François Bareille, Stéphane De Cara, Raja Chakir, Carl Gaigné, Alexandre Gohin, Charlotte Janssens, Pierre Mérel, Guy Meunier, Will Martin, Clément Nedoncelle, and José De Sousa for helpful comments; and to seminar audiences at the NBER Agricultural Markets and Trade Policy, EAERE 2020 annual conference, EAAE 2021 triennial congress, AFSE 2022 annual conference, AgroCampusOuest-SMART, AgroParisTech, University of Illinois, Urbana-Champaign, and SLU. This work is supported by the Convergence Institute CLAND [ANR-16-CONV-0003]. The views expressed herein are those of the author and do not necessarily reflect the views of the National Bureau of Economic Research.

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NBER Working Paper No. 30279
July 2022
JEL No. D58,F18,Q17,Q54,R14

ABSTRACT

A popular approach for estimating climate change impacts on agriculture is to rely on supply-side reduced-form regressions. These methods, which include the Ricardian approach, focus on how farmers and agricultural land market react to changes in climatic conditions, under the implicit assumption that crop prices stay constant. To test whether this assumption is innocuous, I use a quantitative trade model of global agricultural markets to emulate the findings of a supply-side approach as well as to calculate welfare changes accounting for price changes. The results show that both welfare measures are weakly correlated and can be of opposite signs, and that the supply-side approach tends to underestimate the cost of climate change. The main drivers of these differences are the neglects of the imperfect substitutability of crops in demand and of terms-of-trade changes. The supply-side approach provides a valid approximation of the welfare cost of climate change only if crops are almost perfectly substitutable in demand and trade costs are neglected, a situation in which it is reasonable to assume constant prices.

Christophe Gouel
INRAE, Paris-Saclay Applied Economics
AgroParisTech
22 place de l'Agronomie
91120 Palaiseau
christophe.gouel@inrae.fr
France
christophe.gouel@inrae.fr

1 Introduction

Agricultural is one of the most climate-sensitive sectors which makes economic assessment of the consequences of global warming for this sector a crucial component of all analyses of the costs of climate change (Moore et al., 2017). The most popular approaches to carry out this assessment are econometric supply-side studies. They include the Ricardian approach pioneered by Mendelsohn et al. (1994) and the panel-profit approach proposed by Deschênes and Greenstone (2007) which methods have been applied to most countries with available data on farmland values or farm profits (Blanc and Schlenker, 2017; Mendelsohn and Massetti, 2017). The appeal of these approaches rests on their simplicity and transparency. They involve two steps. First, estimating the effect of climatic variables (temperature, precipitation) on farm net revenues or land values using cross-sectional or panel data. Second, combining this estimation with projections of the climatic variables under climate change to obtain the economic effects of climate change through changes in net revenues or land values. In essence, the Ricardian approach is a hedonic approach which considers that market prices, in this case for land, incorporate all the information about relevant local production conditions. Hedonic approaches are best suited to analysis of local issues where changes to amenities are unlikely to affect the market equilibrium and to have feedback effects on the estimated values of these amenities. The amenities considered in the Ricardian approach are the effects of climate on crop growing conditions in terms of land rents. One of the problems related to both this approach and the panel-profit approach is that climate change is not a local issue; its effects are global. If the global impact of climate change is sufficiently heterogeneous between crops, this could lead to large changes in relative crop prices with subsequent effects on valuations of the impact of climate, and could threaten the hedonic foundations of the Ricardian approach.

Despite their popularity, the conditions under which supply-side approaches provide good approximations of the economic effects of climate change are relatively understudied. This paper develops an equilibrium model of global agricultural markets which can be used to analyze welfare assessment differences between a supply-side analysis and an equilibrium analysis. I focus on two sources of potential bias in supply-side approaches. First, neglecting the relative price changes between crops caused by the fact that climate change shocks have heterogeneous effects on crops, and crops are imperfect substitutes. Second, neglect of the terms-of-trade changes caused by climate change. Capturing both effects requires a model with multiple crops and multiple countries. The model used here is close to the model in Gouel and Laborde (2021) which includes all the required elements. I do not carry out supply-side estimations in this paper. The theoretical structure of the equilibrium model is used to mimic a supply-side approach by calculating changes in land rents caused by climate change accounting for farmer adaptations (i.e., switching crops) at constant prices. This approach allows comparison of the welfare under the supply-side approach and the welfare accounting for price adjustments within the same theoretical structure, and allows me to study the conditions of validity of the supply-side approach.

The present paper makes two main contributions. First, it shows that in the general setting of a multi-crop open-economy model, the supply-side approach is likely to provide biased estimates of the welfare effects of climate change. The welfare changes derived from the supply-side approach are weakly correlated with the welfare changes calculated using the equilibrium model. This is explained by the fact that climate change has heterogeneous impacts on crop yields. For some crops yields increase, in others they decrease; thus, if crops are imperfect substitutes this changes their relative prices. These changes in relative prices lead also to terms-of-trade changes depending on the country's trade situation. These effects can be neutralized by assuming that crops are perfect substitutes and trade is costless, conditions under which the approximations enabled by the supply-side approach are not biased.

Second, this paper provides a unified, analytical framework which allows consistent comparison of the three approaches—production function, supply-side, and market equilibrium—generally used for economic analysis of the impacts of global warming on agriculture.[1] The production function approach analyzes the effect of climate change by estimating how much crop yields would change under the new climate accounting for some farm-level adaptations such

[1] In IPCC reports, these approaches would correspond to enumeration, statistical, and CGE methods (see Arent et al., 2014, Table SM10-1). Arent et al. (2014) also refer to the expert elicitation method but to our knowledge it has never been applied to the agricultural sector.

as planting different varieties or adjusting sowing and harvesting periods. Once the yield effects of climate change have been obtained, they can be combined by weighting them using the production values or land rents to convert them into an economic measure of the impact of climate change. In addition to the technological adaptions considered in the production function approach, the supply-side approach accounts also for other farm level adaptations such as switching to more profitable crops but ignores the adaptations related to changes in crop prices which are assumed to be constant (e.g., Mendelsohn et al., 1994; Schlenker et al., 2005, 2006; Deschênes and Greenstone, 2007). Last, the market equilibrium approach accounts also for adaptations mediated by changes in market prices, both within- and between-countries (e.g., Costinot et al., 2016; Gouel and Laborde, 2021).

This work is related to three different research strands. First, it bridges two literatures that adopt very different focuses. For many years, supply-side and market equilibrium approaches had different spatial focuses, and thus, were not comparable. The supply-side approach is applied mostly at country level, and works in this tradition account with details for within-country heterogeneity. Market equilibrium models tend to adopt a global perspective and used to present very limited within-country heterogeneity (e.g., Rosenzweig and Parry, 1994; Darwin et al., 1995; Randhir and Hertel, 2000; Baldos et al., 2019). Studies that employ a supply-side approach take account of adaptations based on within-country reallocation, whereas equilibrium models are focused more on adaptions based on between-country reallocation. The availability of detailed spatial data at world level (e.g., IIASA/FAO, 2021) and increased computational power allow within- and between-country reallocations to be studied in the same equilibrium model as demonstrated by Costinot et al. (2016). In this paper, I build on the recent work of Costinot et al. (2016), which was extended by Gouel and Laborde (2021), and incorporate in the same model the three approaches which have been used to estimate the economic effect of climate change.[2]

Second, this study is related to the large literature analyzing the potential biases of supply-side approaches and how to limit them. Recent contributions include, for example, Ortiz-Bobea (2020) on the bias created by nonfarm influences and Severen et al. (2018) on the role of expectations of future climate change capitalized in land markets (see Ortiz-Bobea, 2021, for a survey of this literature). Lemoine (2021) which is the closest in spirit to this paper analyzes the validity conditions of standard approaches when the true supply-side model is a rich model with intertemporal dynamics and expectations. In this literature, the word bias is commonly used in the econometric understanding of omitted variable bias. However, in the present paper the word bias is used to indicate differences between the outcomes of a model used as a reference (equilibrium model) and the outcomes of a restricted model (supply-side model). The term bias is used similarly by Mendelsohn and Nordhaus (1996) in a comparable setting. Another difference is that the literature discussing potential biases of supply-side approaches assume constant crop prices, the consequences of this assumption have so far been overlooked.

Third, this work is related to works that emphasize the potential bias induced by reduced-form estimations that neglect some key market reactions, for example, Bergquist et al.'s (2019) work on agricultural policy interventions or Heckman et al.'s (1998) study of tuition policy. Both these papers show that when policies are scaled from local to national interventions, general equilibrium effects can lead to very different welfare effects than predicted by the econometric results.

Such critiques of the supply-side approach are not new. It has been clear since at least Cline's (1996) comment that the Ricardian approach refers to a supply-side analysis in which agricultural prices are assumed to remain constant which means that potentially the method is biased (see also the discussion in Auffhammer and Schlenker, 2014). In addition, several articles using trade models show that climate change can generate large terms-of-trade effects which matter crucially for welfare assessments (e.g., Darwin et al., 1995; Baldos et al., 2019; Gouel and Laborde, 2021) and are not accounted for by supply-side analyses. In addition, several empirical articles show that weather shocks are a key determinant of agricultural prices (e.g., Roberts and Schlenker, 2013; Merener, 2015; Ubilava, 2018), which calls into

[2] Darwin's (1999) objective was similar to the objective in this paper: to compare a quantitative general equilibrium model with a Ricardian approach simulated by the model. However, with very limited land heterogeneity (at most 6 land classes per country) and only 4 agricultural sectors using land, the model was unable to capture the rich within-country adjustments which should be captured by the Ricardian approach. In addition, Darwin (1999) does not address the key question of the validity conditions of the Ricardian approach.

question the assumption of constant prices in supply-side approaches. However, Cline's concern that the assumption of constant prices induced a strong bias in the welfare assessments was dismissed by Mendelsohn and Nordhaus (1996), and has been ignored in the subsequent literature on the basis that a simple Marshallian analysis shows that this bias is likely to be small. In section 2, I reproduce Mendelsohn and Nordhaus's example and confirm the authors' finding of a bias that is sufficiently small to be neglected. However, this example is too restrictive so I extend it to an open-economy setting and show that at the country level in the supply-side approach this bias can become arbitrarily large in open economy due to the previously mentioned terms-of-trade effects. Another mechanism can be identified in a two-crop closed-economy general equilibrium model: the neglect by the supply-side approach of the limited substitutability between crops on the demand side can lead to severe biases.

Then, going beyond these simple examples, section 3 presents a parsimonious general equilibrium model centered on the agricultural sector. It is based on Gouel and Laborde's (2021) model and includes features that allow it to mimic a supply-side analysis conducted for every world country, while it can be used also to calculate the welfare effects of climate change accounting for price changes. These two measures of welfare allow me to assess the bias of the supply-side approach in a model accounting for all the potential sources of bias identified in section 2. To allow the model to mimic a supply-side analysis requires two features that are infrequent in trade models applied to the agricultural sector. First, it requires rich within-country spatial heterogeneity as in Costinot et al. (2016) but in contrast to most GTAP-based applications where land is represented by one field per country (Baldos et al., 2019) or a few fields defined by land classes (Darwin et al., 1995), within-country spatial heterogeneity allowing for the within-country reallocations at the heart of the supply-side approach. Here, land is represented by a collection of fields defined as pixels on a 30-arcminute grid, allowing inclusion in the model of 64,858 fields and their individual potential land productivity. Second, it requires several crops with heterogeneous exposure to climate change. A key insight of Mendelsohn et al. (1994) is that climate change is likely to have very different impacts depending on crop and location. The frequent focus in the literature on only the major grains which are important for food security (e.g., Baldos et al., 2019) overlooks the fact that under climate change they might be replaced by crops generating much higher values per hectare. To account for the possibility of crop substitution, the model covers 35 crops including grass to represent pasture, and thus represents most agricultural land uses.

The model is calibrated in section 4. The calibration is similar to that in Gouel and Laborde (2021). For the initial equilibrium, a key data source is the GAEZ project (IIASA/FAO, 2021) which provides information on potential crop yields under current climate and climate change conditions. The behavioral parameters are based on the literature review in Gouel and Laborde (2021) which shows that most studies find small elasticities for food products on the demand and supply sides (see also Fally and Sayre, 2018, for a similar point). While the welfare effects of climate change are obviously very sensitive to the model elasticities, the objective of the paper is not to calculate welfare *per se* but to analyze the conditions under which the welfare change derived from the supply-side approach is a good approximation of exact welfare change. So the chosen calibration serves only as a central case for more detailed discussion of the differences between the supply-side and the equilibrium welfare changes. To mitigate concern about the role of this central calibration, the results using Costinot et al.'s behavioral parameters which represent a situation where demand and supply are more elastic, are provided in a sensitivity analysis (section 6) and confirm the results of the main calibration.

Section 5 presents the results simulated by the quantitative trade model. I consider two sets of results. First, a comparison of the three welfare measures (production function, supply-side, and market equilibrium) obtained with the central calibration. This shows that the production function and supply-side approaches have similar orders of magnitudes since by construction both measures are proportional to the initial land rents. The production function welfare change is inferior to the supply-side welfare since it ignores adaptation related to the land market. The magnitude of market equilibrium welfare change is not necessarily of the same order as the other two measures and depends more on local food scarcity caused by climate change than on initial land rents. In addition, after accounting for market-mediated adaptations, welfare changes can be below or above supply-side welfare changes with possibly different signs. Second, the exploration of the conditions where the supply-side approach provides a good approximation of the equilibrium welfare changes. This is achieved by changing the model assumptions and behavioral parameters, and analyzing how they affect the correlation between the supply-side and exact welfare. The supply-side approach provides an almost perfect approximation of the exact welfare change only if agricultural products are perfect substitutes and trade costs are ignored. Alternative calibrations and scenarios are analyzed in section 6 and confirm the paper's main results.

2 Simple examples

This section presents some simple textbook examples to illustrate the size of the bias in the supply-side approach in various settings. These examples will inform our discussion in the succeeding sections of the respective roles of the various mechanisms. In the examples below, welfare changes from climate change, ΔW, are decomposed into the welfare changes captured by the supply-side approach, ΔW^*, and a bias:

$$\Delta W = \Delta W^* + \text{Bias}. \tag{1}$$

The counterfactual value after climate change of the variable v is denoted v', and the counterfactual value under the supply-side approach is denoted v^*.

2.1 Single country model

To begin, consider an example discussed in Mendelsohn and Nordhaus (1996) in a response to Cline's (1996) comment that neglect of price changes induces a bias in the Ricardian approach. Mendelsohn and Nordhaus (1996) propose an analysis of the bias related to neglecting price changes using a simple Marshallian approach in a closed economy. They use linear demand and supply curves to represent the agricultural sector, explain that climate change can be represented by a shift to the left of the supply curve, and define in this setting the Ricardian approach as the change in the producer surplus at constant prices. This assessment neglects the price increase which leads to a reduction in demand and an increase in supply that is lower than the initial shock, and a small bias: the Ricardian approach underestimates the welfare loss from a negative climate change shock. Figure 1 reproduces their example but assumes that climate change can be represented by a pivotal shift to the left of the supply curve. This assumption barely changes the intuitions but ensures consistency with the full model presented in section 3,

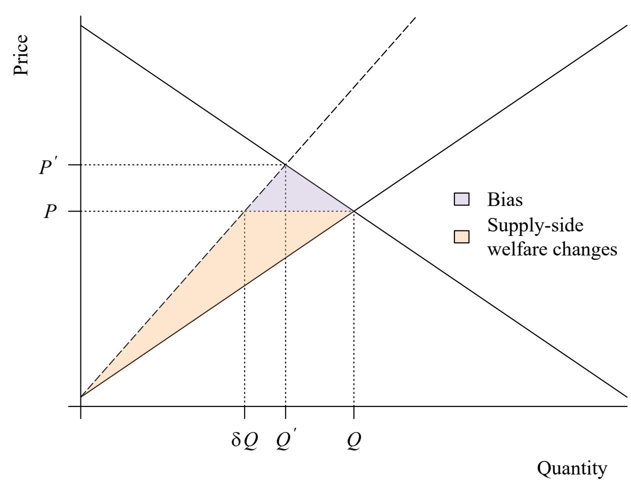


Figure 1: Bias of the supply-side approach in a closed-economy. Initial equilibrium (Q, P) and equilibrium after climate change (Q', P'). Climate change is represented as a pivotal shift to the left of the supply curve reducing production at constant price to δQ.

Mathematically, the ratio of the bias to total welfare changes is given by[3]

$$\frac{\text{Bias}}{\Delta W} = \frac{\eta\,(1-\delta)}{\epsilon+\eta}, \tag{2}$$

where $\eta, \epsilon > 0$ are the supply elasticity and the negative of demand elasticity at initial equilibrium, and δ is the size of the climate change shock expressed as a deviation from the initial equilibrium such that $\delta = 1$ represents the absence of a shock and $\delta < 1$ represents a negative supply shock. The bias is positive for a negative supply shock and negative for a positive supply shock. Therefore, the supply-side approach underestimates the welfare costs of a negative climate change shock. The bias increases in absolute value with the values of the demand and supply elasticities and its limit if $\epsilon \to 0$ or $\eta \to +\infty$ is $1-\delta$. So, for a 10% reduction in the supply the bias does not exceed 10% of the total losses. These results confirm the intuition from figure 1 that in a closed economy compared to total losses the bias is small.[4]

Note though that by construction, the supply-side approach focuses on assessing efficiency losses and cannot assess the distributive effects of climate change. In this example, these would be the transfers from producers to consumers because of the higher prices, and are equal to $(P'-P)Q'$. Figure 1 shows that these transfers could be sizable. The fact that transfers are neglected is inconsequential in the case of a closed economy, but explains how the bias can increase in an open economy.

2.2 Two-country model

Now let us consider a two-country extension of the previous linear model. Home, indexed h, is the exporter and Foreign, indexed f, is the importer. Assume that in equilibrium under current climate conditions, demand and supply elasticities are the same for both countries. Climate change is represented by a pivotal shift in the supply of curves of, respectively, δ_h and δ_f. Figure 2 represents the situation with a climate change shock of the same relative intensity in each country ($\delta = \delta_h = \delta_f$).

The size of the bias in the supply-side approach increases from a triangle in a closed economy to two trapezoids in an open economy with one base related to the size of trade under climate change. In figure 2 in Home, the exporting country, the bias is negative.[5] The supply-side approach overestimates the welfare losses by neglecting the fact that an exporter can be partly compensated for its reduced production by a price increase. Conversely, the bias in Foreign is positive but larger than in autarky. The supply-side welfare loss from a shift in the supply curve is aggravated by the increased importing costs. In this setting, the size of the bias is larger in absolute value for the importer compared to the exporter. Since the biases have opposite signs, they are partially canceled out if summed, and the aggregate bias is the same as that obtained for the previous one-country model.

Assuming the same shock in both countries, the relative biases are

$$\frac{\text{Bias}_h}{\Delta W_h} = \frac{\eta\,\{(1-\delta)\,(\epsilon+\delta\eta) - x_h\,[2\delta\eta + (1+\delta)\,\epsilon]\}}{\epsilon^2 - \delta\eta^2 + \eta\,(1-x_h)\,[(1+\delta)\,\epsilon + 2\delta\eta]}, \tag{3}$$

$$\frac{\text{Bias}_f}{\Delta W_f} = \frac{\eta\,\left\{(1-\delta)\,(\epsilon+\delta\eta) + m_f\,[2\delta\eta + (1+\delta)\,\epsilon]\right\}}{\epsilon^2 - \delta\eta^2 + \eta\left(1+m_f\right)[(1+\delta)\,\epsilon + 2\delta\eta]}, \tag{4}$$

where $x_h = (Q_h - C_h)/Q_h$ and $m_f = (C_f - Q_f)/Q_f$ are the ratios of Home export and Foreign import to domestic production. The biases are composed of two terms: efficiency triangles and terms-of-trade effects. Since the efficiency triangles always contribute positively to biases, Home bias can be positive, null, or negative depending on the initial

[3]Since producer surplus can be biased when evaluating the effect of technological change (see Martin and Alston, 1997, for a demonstration), the welfare calculations for this example and the next are based on producer profit, the surplus approach being only kept on the figure for illustrative purpose. Welfare is calculated assuming $p(d) = P[1-(d/Q-1)/\epsilon]$ for the inverse demand function and $P[(1-1/\eta)q + q^2/(2\delta\eta Q)]$ for the producer's variable cost.

[4]Under the horizontal shift of Mendelsohn and Nordhaus (1996), the relative bias is even smaller with $\text{Bias}/\Delta W = \eta(1-\delta)/[\epsilon(1+\delta)+2\eta]$.

[5]The bias is not necessarily either negative or trapezoid for the exporting country. For small shocks, it can be positive and can be represented by 2 triangles.

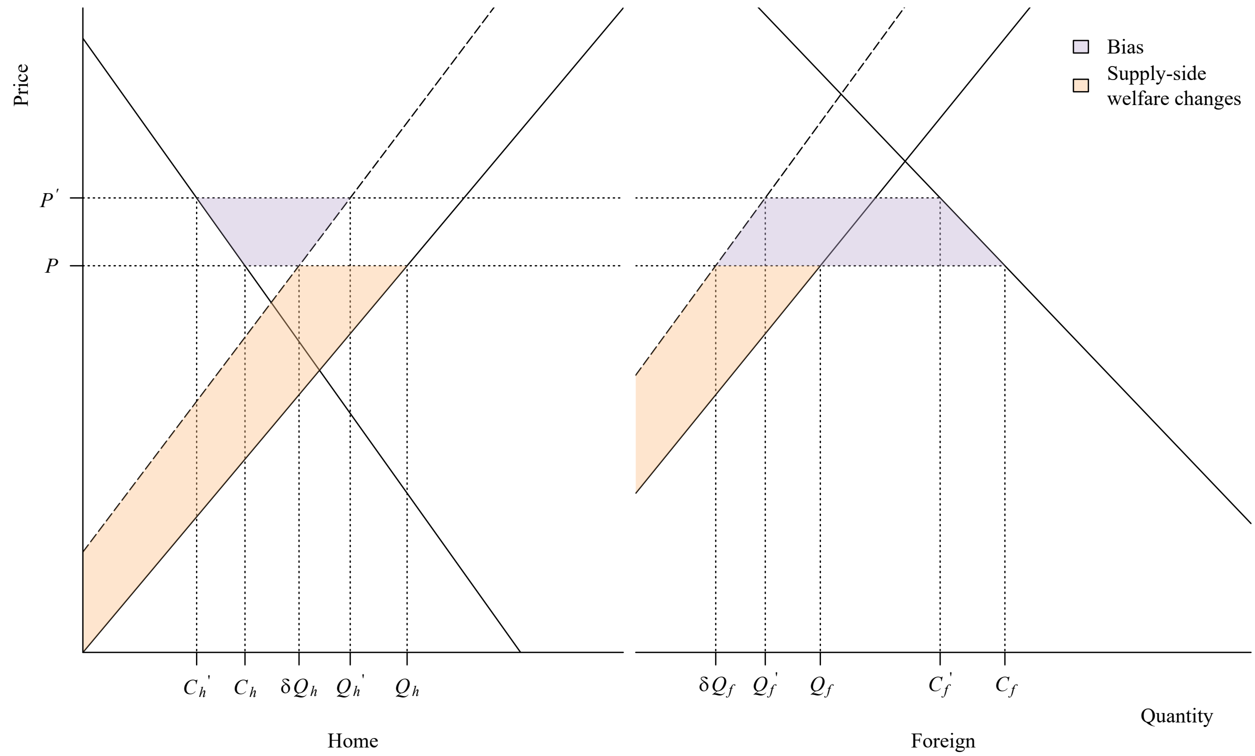


Figure 2: Bias of the supply-side approach in a two-country model. Initial equilibrium (C_h, C_f, Q_h, Q_f, P) and equilibrium after climate change $(C_h', C_f', Q_h', Q_f', P')$. Climate change is represented as a pivotal shift of the supply curves by δ.

share of export in production. For an export share lower than $(\eta + \delta\epsilon)(1-\delta)/[2\delta\eta + (1+\delta)\epsilon]$, the bias is positive, and turns negative for higher export shares.

While it is also possible to characterize the biases analytically in the case of different shocks between countries, the expression of the biases is cumbersome. Instead, I provide a numerical illustration of the size of the biases under the various symmetric and asymmetric shocks situations presented in table 1. In this case, the global shock can be defined as $\delta = (Q_h\delta_h + Q_f\delta_f)/(Q_h + Q_f)$, with δ_h and δ_f the country-level shocks. The central case (table 1 case 1) is the situation of symmetric shocks with $\delta = 0.9$, $\epsilon = 0.5$, $\eta = 0.5$, and $x_h = m_f = 0.25$. In this case, the bias is negative for Home, since the export share threshold under which the bias is negative is equal to 5.1%.

Table 1 presents the bias for each country individually and combined. It confirms Mendelsohn and Nordhaus's (1996) results that the world bias is always small and positive. It is affected not by the share exported or the allocation of the shock between countries but only by the global shock and the elasticities. The country-level biases are one or two orders of magnitude higher but since they have opposite signs they tend to compensate one another at the global level. If we compare cases 1–8, the size of the bias at the country and global levels increases with a more inelastic demand or a more elastic supply. The influence of elasticities on country-level biases depends on the asymmetry of the shocks. For symmetric shocks (cases 1–5), the elasticities have symmetric effects on the bias. For asymmetric shocks (cases 6–8), the true welfare loss of Home is small due to large terms-of-trade changes which are neglected in the supply-side approach resulting in overestimation of the losses by at least a factor of 2. Further decreasing demand elasticity or increasing supply elasticity brings Home welfare losses closer to zero, greatly increasing the relative bias.

Asymmetric shocks leave the global bias unaffected but increase the bias in one country and reduce it in the other. For example, if the shock to the exporting country is smaller than the shock at the global level (cases 6–8 and 13–14),

Table 1: Illustration of bias in a two-country model

Case $(\delta, \epsilon, \eta, x_h)$ [a]	Home bias $\text{Bias}_h/\Delta W_h$ (%)	Foreign bias $\text{Bias}_f/\Delta W_f$ (%)	World bias $(\text{Bias}_h + \text{Bias}_f)/(\Delta W_h + \Delta W_f)$ (%)
1. (0.90, 0.5, 0.5, 0.25)	−25.6	23.6	5.0
2. (0.90, 1.0, 0.5, 0.25)	−15.2	16.7	3.3
3. (0.90, 0.2, 0.5, 0.25)	−43.2	31.3	7.1
4. (0.90, 0.5, 1.0, 0.25)	−38.8	30.0	6.7
5. (0.90, 0.5, 0.2, 0.25)	−12.6	14.6	2.9
6. (0.90, 0.5, 0.5, 0.25, $\delta_h = 0.95$)	−106.3	19.5	5.0
7. (0.90, 0.2, 0.5, 0.25, $\delta_h = 0.95$)	−322.5	26.3	7.1
8. (0.90, 0.5, 1.0, 0.25, $\delta_h = 0.95$)	−240.1	24.9	6.7
9. (0.90, 0.5, 0.5, 0.25, $\delta_h = 0.85$)	−11.1	33.8	5.0
10. (0.90, 0.5, 0.5, 0.50)	−85.1	36.1	5.0
11. (0.75, 0.5, 0.5, 0.25)	−14.0	29.0	12.5
12. (0.75, 0.5, 0.5, 0.50)	−63.3	40.2	12.5
13. (0.75, 0.5, 0.5, 0.25, $\delta_h = 0.90$)	−326.1	27	12.5
14. (0.75, 0.5, 0.5, 0.50, $\delta_h = 0.90$)	333.3	34.9	12.5

Notes: It is assumed that Home and Foreign have the same production levels under current climate conditions, so $x_h = m_f$.
[a] $(\delta, \epsilon, \eta, x_h)$ respectively denote the size of the global production shock (no global shock is $\delta = 1$), the opposite of the elasticity of demand, the elasticity of supply, and the share of export in Home production.

the bias becomes more important in the exporting country, with the supply-side welfare displaying the wrong sign in case 14. In this case, the supply-side approach predicts a welfare loss while the increase in the value of exports is so large that Home benefits from climate change.

Increasing the size of the aggregate shock has ambiguous effects. Comparing cases 1 and 11, the bias decreases in Home and increases in Foreign with a larger shock. This is because the bias is the sum of two terms, one common to both countries and with a positive sign corresponding to the global bias, and one specific to the trade situation and with opposite signs corresponding to the terms of trade. In the case of a larger shock, the first term increases more than the second and the exporting country bias decreases.

The final parameter of interest is exported share. As expected, the size of the bias increases with the share exported (cases 1 and 10–14) because this determines the size of the terms-of-trade effects in equations (3) and (4).

This toy model clarifies some of the main parameters that tend to drive a large bias in open economy in the supply-side approach. These parameters are the size of the climate change shock, the between-country dispersion of the shock, the countries' trade share, and the elasticities.

Since the terms-of-trade effects cancel out at the world level, a supply-side approach applied at the world level would have the small bias identified in the single-country example. In practice, given its heavy data requirements, this method is generally applied at the country level or, with a few exceptions at the continental level (Kurukulasuriya et al., 2006, apply it to 11 African countries, and Passel et al., 2017, apply it at the European level). Thus, the bias created by terms of trade cannot be eliminated. In addition, the next example shows that even in a closed economy there is another source of large bias.

2.3 Two-crop model

Consider a closed economy general equilibrium model where two crops, indexed $k = 1, 2$, can be produced from a land endowment L.[6] Utility, U, is CES over the two crops:

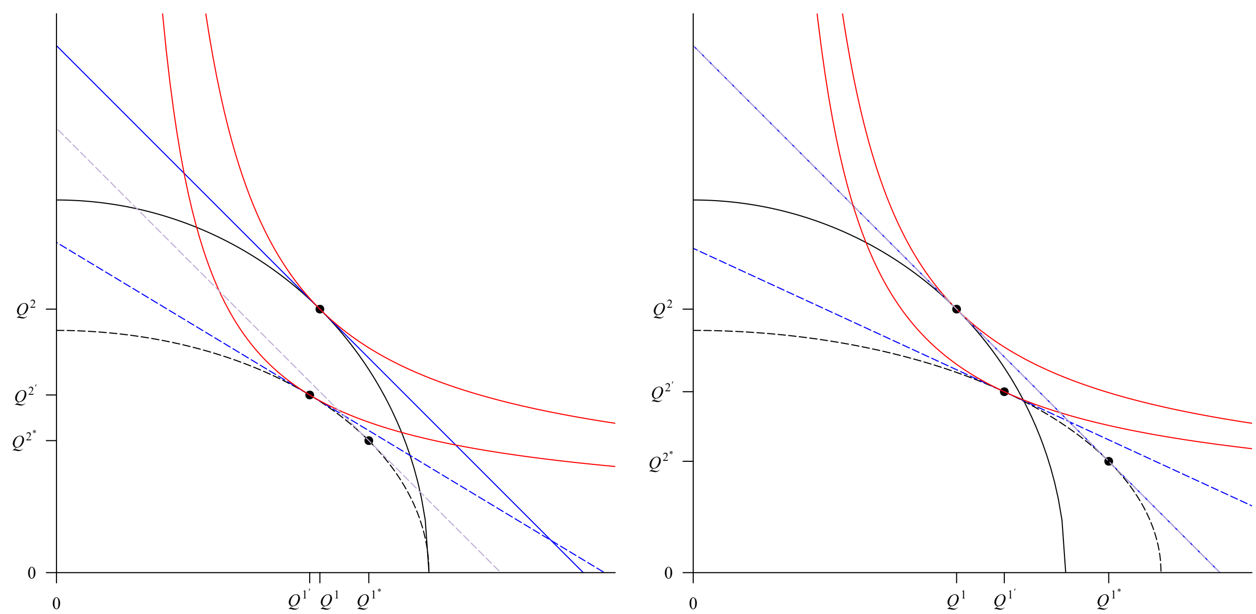
$$U = \left[\sum_{k=1}^{2} \left(\beta^k \right)^{1/\kappa} \left(C^k \right)^{(\kappa-1)/\kappa} \right]^{\kappa/(\kappa-1)}, \tag{5}$$

where C^k is crop-k consumption, $\kappa > 0$ and $\neq 1$ is the elasticity of substitution between crops, and $\beta^k \geq 0$ is a preference shifter. Land is imperfectly substitutable between the two crops according to the following Constant Elasticity of Transformation function

$$L = \left[\sum_{k=1}^{2} \left(A^k \right)^{-\theta/(\theta-1)} \left(Q^k \right)^{\theta/(\theta-1)} \right]^{(\theta-1)/\theta}, \tag{6}$$

where Q^k is crop-k production, equal via market clearing to C^k, $\theta > 1$ parameterizes the transformation of land between the two crops, and $A^k \geq 0$ are productivity shifters. Climate change is represented as a shock to the productivity shifters, with values under climate change given by $A^{k\prime} = \delta^k A^k$.

Figure 3 depicts the model behavior under two different climate change shocks. Climate change leads to changes in the production possibility frontier (PPF). Under the assumption of constant prices, production under the supply-side approach, (Q^{1^*}, Q^{2^*}), is located on the tangent of the new PPF and a budgetary constraint relying on benchmark prices. Depending on the shock, the elasticity of substitution, and the elasticity of transformation, production under the supply-side approach can be distant from or close to true production under climate change.



(a) Smaller welfare losses with the supply-side approach because of the neglect of the imperfect substitution between crops.

(b) No welfare changes with the supply-side approach because at constant prices the increased productivity of crop 1 compensates for the decreased productivity of crop 2.

Figure 3: Two illustrations of the supply-side approach with the two-crop model

[6]Note that the calculations that follow are valid whatever the number of crops.

In this setting and using α^k to denote the budget share of crop k under the current climate, Appendix A shows that the ratio of the bias to total welfare changes is given by

$$\frac{\text{Bias}}{\Delta W} = 1 - \frac{\left[\sum_{k=1}^{2} \alpha^k \left(\delta^k\right)^{\theta}\right]^{1/\theta} - 1}{\left[\sum_{k=1}^{2} \alpha^k \left(\delta^k\right)^{1/[1/\theta+1/(\kappa-1)]}\right]^{1/\theta+1/(\kappa-1)} - 1}. \tag{7}$$

Expressing the bias in this way highlights the following. (i) The supply-side (numerator) and true welfare changes (denominator) are expressed similarly but the elasticity of substitution between crops appears in the true welfare change but not in the welfare change under the supply-side approach. (ii) Because $\kappa > 0$ then by generalized means inequality, the utility under the supply-side approach is always superior to or equal to the true utility under climate change, so the supply-side approach underestimates the cost of climate change. (iii) If crops are perfectly substitutable (i.e., $\kappa \to \infty$), then there is no bias and the supply-side approach delivers the exact welfare changes. (iv) If the shock is uniform across crops, $\delta = \delta^k$, then there is no bias. In both (iii) and (iv), the assumption of constant (relative) prices is satisfied and the shock can be summarized by an income shock evaluated on land rents. For further intuitions on the bias, I provide numerical illustrations below.

Table 2 presents the model behavior by varying θ, κ, and the δ^k in a setting where the crops have initially the same budget share. Table 2 presents the aggregate first-order shock, $\delta = \sum_{k=1}^{2} \alpha_k \delta^k$, the welfare change under the supply-side approach, the true welfare change, and the supply-side approach bias. In line with the theoretical predictions, the supply-side approach always leads to underestimation of the losses, and thus a positive bias. In contrast to the previous examples, the size of the bias is unrelated to the size of the shock but is related to the heterogeneity of the shocks across crops, mediated by the elasticities of substitution and transformation. If we compare cases 1 and 4 we find that for the same shock dispersion around the average (measured as standard deviations), the bias is smaller for a larger shock. In cases 1–3, only the dispersion of the shock changes and the bias increases from 0% to 43.1%. In case 5 where the first-order shock is zero because the productivity increase in one crop compensates for the productivity decrease in the other crop, the bias exceeds 100 meaning that the welfare change under the supply-side approach has the wrong sign. It should be noted that case 2 where the supply-side approach contains no bias is a case where the supply-side approach has no interest because it is equivalent to a simple production function approach: $\delta - 1 = \Delta W^*/L$.

Table 2: Illustration of bias in a two-crop model

Case $(\theta, \kappa, \delta^1, \delta^2)$[a]	$\delta - 1$ (%)	$\Delta W^*/L$ (%)	$\Delta W/L$ (%)	Bias/ΔW (%)
1. (2.0, 0.5, 1.00, 0.80)	−10.0	−9.4	−10.9	13.6
2. (2.0, 0.5, 0.90, 0.90)	−10.0	−10.0	−10.0	0
3. (2.0, 0.5, 1.10, 0.70)	−10.0	−7.8	−13.7	43.1
4. (2.0, 0.5, 0.85, 0.65)	−25.0	−24.3	−26.1	6.8
5. (2.0, 0.5, 1.20, 0.80)	0	2.0	−3.3	159.1
6. (2.0, 1.5, 1.00, 0.80)	−10.0	−9.4	−10.3	8.6
7. (2.0, 5.0, 1.00, 0.80)	−10.0	−9.4	−9.8	3.8
8. (1.5, 0.5, 1.00, 0.80)	−10.0	−9.7	−11.0	11.4
9. (3.0, 0.5, 1.00, 0.80)	−10.0	−8.9	−10.9	18.3
10. (9.0, 0.5, 1.00, 0.80)	−10.0	−6.1	−10.9	43.7
11. (2.0, 0.7, 1.00, 0.65)	−17.5	−15.7	−20.0	21.8
12. (2.0, 0.7, 1.26, 0.65)	−4.7	0	−11.4	100.0

Notes: Initial budget shares are assumed to be the same under current climate conditions, so $\alpha^k = 0.5$. [a] $(\theta, \kappa, \delta^1, \delta^2)$ respectively denote 1 minus the elasticity of transformation between crops, the elasticity of substitution between crops, and the size of the production shocks (no shock is $\delta^k = 1$).

Cases 11 and 12 correspond to the depictions in Figures 3a and 3b, respectively. Case 12 and figure 3b describe a peculiar case of the bias created by neglect of the imperfect substitution between crops on the demand side. It considers shocks such that $[\sum_{k=1}^{2} \alpha^k (\delta^k)^\theta]^{1/\theta} = 1$, that is a situation where welfare is unchanged in the supply-side approach because the increased productivity of one crop compensates exactly for the decreased productivity of the other crop. Then by construction, the supply-side approach relative bias is 100%. In this case, the true welfare loss is 11.4‰ because if consumers consider the crops as imperfectly substitutable an increase in the production of one crop cannot compensate the decrease of the other.

θ has a limited effect on true welfare changes (lower than the number of digits printed in table 2), but a bigger effect on welfare changes under the supply-side approach, so the bias increases with θ (cases 1 and 8–10). Although the supply-side approach accounts for a reallocation between crops because of productivity changes, and thus depends on the value of θ, this does not free the bias from the influence of θ because the effect of the relative price changes on crop reallocation is mediated also by θ.

Lastly, as expected, the bias decreases with the elasticity of substitution, κ. Here the effect is opposite to the case of θ. κ has no effect on welfare under the supply-side approach but decreases the true welfare losses thereby decreasing the bias (cases 1, 6, and 7).

This two-crop model is an example of a closed economy with no other goods than these crops (so with inelastic demand for the crop bundle), and with no possibility to produce more of one crop without producing less of the other (so no aggregate supply elasticity). Hence, it neglects the biases analyzed in the two previous examples. In more realistic settings including all these adjustment margins, all these biases would be compounded.

Finally, I would like to highlight two issues. First, by Jensen inequality, the supply-side approach leads to welfare losses lower than obtained in a production function approach represented in table 2 in the column $\delta - 1$. Second, true welfare can be below or above that obtained using the production function approach, depending on the parameter values. It exceeds the production function welfare if $\kappa \geq 1 + \theta/(\theta - 1)$. For a sufficiently high κ as in case 7, true welfare converges to welfare under the supply-side approach with welfare losses lower than predicted by the production function approach.

2.4 Summary of the findings from textbook examples

Based on these examples, the following tentative conclusions can be drawn. Overall, the supply-side approach should lead to an under-evaluation of the costs of climate change due to neglect of imperfect substitution between crops (section 2.3), and the neglect of the reactions of the overall market (section 2.1). However, if terms-of-trade effects are sufficiently large, the signs on the bias in the supply-side approach can change for exporting countries leading to an over-evaluation of the losses for large food exporters (section 2.2). Since the terms of trade are only transfers between countries, they do not affect the average under-evaluation at the world level.

3 Model

This section presents a model of global agricultural trade and land use which can be used to mimic the results of an ideal supply-side approach and to calculate exact welfare changes. The model follows Gouel and Laborde's (2021) framework with one difference: how the substitution between land and non-land inputs in crop production is accounted for. The model includes all the potential sources of bias discussed previously, and two additional sources. It uses the notations employed in section 2, and interprets the elasticities in the same way. The model structure is simpler than many of the GTAP-based CGE models used in this literature (e.g., Darwin, 1999; Baldos et al., 2019). Among the many differences from these models, my model assumes demand for food that is inelastic to income, a constant price for the non-land input used in crop production, and a fixed agricultural land area. The specific roles of these assumptions are discussed later in the paper, but all limit the general equilibrium mechanisms to the agricultural sector. In developed countries where the agricultural sector represents a small share of economic activities these assumptions will likely be innocuous. This is less the case for developing countries but neglect of these mechanisms is a minor issue given the objective of the present paper. The supply-side approach also neglects these general equilibrium mechanisms, so these modeling choices limit the bias in the supply-side approach to the previously identified mechanisms which are likely to be among the most important ones.

Agents are endowed with land and some labor, and are assumed to supply their labor without friction within a country but cannot move between countries. All markets are perfectly competitive. Countries are indexed by i or $j \in \mathcal{I}$. Agricultural land in country i comprises F_i heterogeneous fields indexed $f \in \mathcal{F}_i$ of surface area s_i^f, and each composed of a continuum of parcels indexed $\omega \in [0, 1]$. The labor endowment in country i is N_i. Goods are denoted $k \in \mathcal{K}$. The outside good which represents all non-agricultural goods is denoted $k = 0$. It is freely traded and acts as the numeraire. Agricultural goods include the crops defined by the set $\mathcal{K}^c \subset \mathcal{K}$ and one livestock products sector indexed $k = l$. Crop production requires land and labor and uses all available agricultural land. Livestock production requires land indirectly through demand for feed including grass. Grass is a specific crop for three reasons. First, its production requires only land, making it a default choice if the labor costs related to other crops exceeds the local potential productivity of the land. Second, it is assumed to be non-tradable because it represents forage crops which are grazed directly by animals, and fodder crops (e.g., alfalfa hay) whose value-to-weight ratio is too low to be tradable. Third, it is used only to feed livestock. All agricultural goods, except grass, are gathered in the set $\mathcal{K}^a \subset \mathcal{K}$.

3.1 Households

The representative household in country j has quasi-linear preferences over the consumption of the non-agricultural good denoted C_j^0 and the bundle of agricultural goods denoted C_j:

$$U_j = C_j^0 + \beta_j^{1/\epsilon} \begin{cases} C_j^{1-1/\epsilon}/(1-1/\epsilon) & \text{if } \epsilon \neq 1, \\ \ln C_j & \text{if } \epsilon = 1, \end{cases} \tag{8}$$

where $\epsilon > 0$ is the opposite of the price elasticity of demand for the agricultural bundle and $\beta_j > 0$ parameterizes demand for the agricultural bundle. For parsimony, I assume a demand for agricultural goods that is inelastic to income. In developed countries where the share of income from the agricultural sector and the budget share of primary agricultural products are small, this assumption is likely to have limited impacts. For developing countries, if the climate change shock is enough to affect these shares, then the model will tend to underestimate any welfare losses. This assumption is easily relaxed as is common in the structural change literature (Comin et al., 2021). In the context of this paper, this assumption implies that the model neglects a mechanism that is also neglected by the supply-side approach, thus limiting the bias that can be evaluated.

The bundle of agricultural goods is a CES composite:

$$C_j = \left[\sum_{k \in \mathcal{K}^a} \left(\beta_j^k\right)^{1/\kappa} \left(C_j^k\right)^{(\kappa-1)/\kappa} \right]^{\kappa/(\kappa-1)}, \tag{9}$$

where $\kappa > 0$ and $\neq 1$ is the elasticity of substitution between agricultural products, C_j^k is the final consumption of product k, and $\beta_j^k \geq 0$ is an exogenous preference parameter.

Given households' quasi-linear preferences in equation (8) and assuming an interior solution where income is high enough to ensure a strictly positive consumption level of the outside good, utility maximization implies the following demand for the bundle of agricultural products:

$$C_j = \beta_j P_j^{-\epsilon}, \tag{10}$$

where P_j is the price of the bundle of agricultural goods given by

$$P_j = \left[\sum_{k \in \mathcal{K}^a} \beta_j^k \left(P_j^k \right)^{1-\kappa} \right]^{1/(1-\kappa)}, \tag{11}$$

and where P_j^k is the composite price of imports of good k.

From equation (9), demand for the product bundle $k \in \mathcal{K}^a$ is given by

$$C_j^k = \beta_j^k \left(\frac{P_j^k}{P_j} \right)^{-\kappa} C_j. \tag{12}$$

3.2 International trade

Regarding the representation of international trade, I consider two approaches: an Armington assumption and a homogeneous good assumption. Under both assumptions, domestic trade costs are neglected and all producers in a region receive the same price for a crop. This applies also to grass which is assumed only to be non-tradable internationally. This assumption of perfect mobility within a country greatly simplifies the modeling of livestock by avoiding the need to represent livestock production by field.

The Armington assumption, combined with multiplicative trade costs, leads to a standard gravity specification for trade. It means also that any deviation from the initial trade pattern will have an effect on the import price index, exacerbating the terms-of-trade effects and the potential bias of the supply-side approach as analyzed in section 2.2. To avoid this additional bias and allow the model to exactly replicate the supply-side approach, I also consider a version where agricultural goods are assumed to be homogeneous products.

Under the Armington assumption, with the exception of the outside good international trade entails iceberg trade costs. $\tau_{ij}^k \geq 1$ units must be shipped from country i to country j in order to achieve the sale of one unit of the variety of sector k. The absence of arbitrage opportunities implies that

$$p_{ij}^k = \tau_{ij}^k p_i^k \text{ for all } k \in \mathcal{K}^a, \tag{13}$$

where p_i^k is the producer price of good k in region i and p_{ij}^k is its import price in region j. The CES preferences regarding the countries of origin are assumed to be similar for final and intermediate consumption so the index price aggregating the price of varieties from different origins is

$$P_j^k = \left[\sum_{i \in \mathcal{I}} \beta_{ij}^k \left(\tau_{ij}^k p_i^k \right)^{1-\sigma} \right]^{1/(1-\sigma)} \text{ for all } k \in \mathcal{K}^a, \tag{14}$$

where $\sigma > 0$ and $\neq 1$ is the elasticity of substitution among the varieties from different regions, and $\beta_{ij}^k \geq 0$ is an exogenous preference parameter.

Total import demand is equal to the sum of the demand for final consumption and livestock feed, x_j^k, if relevant:

$$X_j^k / P_j^k = C_j^k + \mathbf{1}_{k \in \mathcal{K}^c} \left(x_j^k \right) \text{ for all } k \in \mathcal{K}^a, \tag{15}$$

where X_j^k is the value of imports and $\mathbf{1}_{(\cdot)}$ is the indicator function. Lastly, the value of exports of good $k \in \mathcal{K}^a$ from country i to country j is given by

$$X_{ij}^k = \beta_{ij}^k \left(\frac{\tau_{ij}^k p_i^k}{P_j^k} \right)^{1-\sigma} X_j^k. \tag{16}$$

Under the homogeneous good assumption, I assume away trade costs implying a situation of integrated world markets for agricultural products. In this case, prices are the same in every country:

$$p_{ij}^k = p_i^k = p_j^k \text{ for all } k \in \mathcal{K}^a. \tag{17}$$

3.3 Producers

3.3.1 Non-agricultural good

The non-agricultural good is produced using only labor and with constant returns to scale where $A_i^0 > 0$ represents labor productivity. The combination of zero profit, absence of trade barriers, and the numeraire assumption in the non-agricultural sector implies equality between wages, w_i, and A_i^0, and is exploited below to substitute away w_i.

3.3.2 Crops

Crops are produced using land and labor combined using a CES function with elasticity $\eta \geq 0$.[7] If the crop $k \in \mathcal{K}^c$ is planted on the parcel ω, production is given by

$$Q_i^{fk}(\omega) = \left\{ \left[A_i^{fk}(\omega)\, L_i^{fk}(\omega) \right]^{(\eta-1)/\eta} + \left[A_i^{Nk} N_i^{fk}(\omega) \right]^{(\eta-1)/\eta} \right\}^{\eta/(\eta-1)}, \tag{18}$$

where $L_i^{fk}(\omega)$ is the area of the parcel, $A_i^{fk}(\omega) \geq 0$ and $A_i^{Nk} > 0$ parameterize the productivity of land and labor, and $N_i^{fk}(\omega)$ is the quantity of labor used in production. $A_i^{fk}(\omega)$ is assumed to be i.i.d. from a Fréchet distribution with shape $\theta > 1$ and scale $\gamma A_i^{fk} > 0$, where $\gamma \equiv [\Gamma(1 - 1/\theta)]^{-1}$ is a scaling parameter such that $A_i^{fk} = \mathrm{E}[A_i^{fk}(\omega)]$ and $\Gamma(\cdot)$ is the Gamma function. θ characterizes the heterogeneity within fields, with a higher θ indicating higher levels of homogeneity.

I assume that the production of grass does not require any labor. This assumption makes grass the default choice if the productivity of the other crops is not sufficiently high, and the corresponding labor costs are so high they preclude their cultivation. This is consistent with pastures being more likely to be located on land that is not best suited to crop production due to short growing seasons, limited access to water, or steep gradients. However, this assumption neglects the fact that pastures and hay fields are managed actively and are not simply rangelands. This problem is related to data availability. Agricultural statistics usually are unable to distinguish among rangelands, pasture, and hay fields since along a continuum of management practices the crops are similar which provides little information on which to base any distinction.[8]

In this model, the aggregate supply elasticity of the agricultural sector (similar to the representations in sections 2.1 and 2.2) is represented by the possibility to intensify production through use of additional labor, and is controlled by η. An alternative could be to introduce an extensive land margin and allow agricultural land to expand over other land uses (e.g., forest). To be consistent with most of the supply-side literature, I ignore this extensive margin. The supply-side approach focuses on the effect of climate change on the agricultural sector. Thus, it neglects this extensive margin which would require information on the effect of climate change on other land-using sectors.[9] This implies that there is no need to represent other land uses in the model because the surface of each field s_i^f is restricted to its initial surface used to grow crops or for pasture.

[7]For conciseness, only the equations associated to a CES are presented in the text, but the model is adjusted to the Leontief and Cobb-Douglas cases which also are considered in the simulations.

[8]Since grass production requires no any labor, it can be increased only by taking away land from other crops. From the analysis in sections 2.1 and 2.2, the impossibility to intensify production is equivalent to assuming $\eta = 0$ for grass, so this assumption should reduce the bias of the supply-side approach.

[9]Timmins (2005) is an exception since he accounts for the possible extension of agricultural land to forests.

The CES structure of crop production implies that the output price is given by the CES price index:

$$p_i^k = \left\{ \left[r_i^{fk}(\omega) / A_i^{fk}(\omega) \right]^{1-\eta} + \left(w_i / A_i^{Nk} \right)^{1-\eta} \right\}^{1/(1-\eta)}, \tag{19}$$

where $r_i^{fk}(\omega)$ is defined as the per hectare land rents. Land rents can be expressed as the residual of crop revenue after subtracting the cost of labor:

$$R_i^{fk}(\omega) = p_i^k Q_i^{fk}(\omega) - w N_i^{fk}(\omega) = r_i^{fk}(\omega) L_i^{fk}(\omega). \tag{20}$$

Defining

$$r_i^k \equiv r_i^{fk}(\omega) / A_i^{fk}(\omega) = \left[\left(p_i^k \right)^{1-\eta} - \left(A_i^0 / A_i^{Nk} \right)^{1-\eta} \right]^{1/(1-\eta)}, \tag{21}$$

the land rents can be expressed as function of the variables exogenous to the landowner's decision:

$$R_i^{fk}(\omega) = A_i^{fk}(\omega) L_i^{fk}(\omega) r_i^k. \tag{22}$$

To maximize its profit, the landowner plants a parcel of land with the crop that delivers the highest land rent, $R_i^k(\omega)$. Given that land rents follow a Type-II extreme value distribution, the decision about how to allocate land involves a discrete choice problem and the probability that crop k is the most profitable crop is given by

$$\pi_i^{fk} = \frac{\left(r_i^k A_i^{fk} \right)^{\theta}}{\sum_{l \in \mathcal{K}^c} \left(r_i^l A_i^{fl} \right)^{\theta}}, \tag{23}$$

where $r_i^k A_i^{fk}$ is a measure of the unconditional land rents. Since each field includes a continuum of parcels with the same probability of acreage choice, π_i^{fk} is also the share of field f in country i planted with crop k.

Using standard CES and Fréchet algebra, the total output of crop k by field f is given by

$$Q_i^{fk} = s_i^f A_i^{fk} \left(\pi_i^{fk} \right)^{(\theta-1)/\theta} \left(\frac{r_i^k}{p_i^k} \right)^{\eta}. \tag{24}$$

Output is the product of the field surface, the share of acreage devoted to crop k, and the average yield,

$$y_i^{fk} = A_i^{fk} \left(\pi_i^{fk} \right)^{-1/\theta} \left(\frac{r_i^k}{p_i^k} \right)^{\eta}, \tag{25}$$

and includes a composition effect related to the assignment of parcels to their most profitable use and an intensification effect related to the possibility to increase yields by using more labor. A_i^{fk} parameterizes the yields. Its value is calibrated on information on potential yields from the GAEZ project (IIASA/FAO, 2021) and is shocked to represent the effect of climate change.

From equation (24), country-level production is obtained by summing field-level production:

$$Q_i^k = \left(\frac{r_i^k}{p_i^k} \right)^{\eta} \sum_{f \in \mathcal{F}_i} s_i^f A_i^{fk} \left(\pi_i^{fk} \right)^{(\theta-1)/\theta}, \tag{26}$$

and total land rents are given by

$$R_i^k = \left(p_i^k\right)^{\eta} \left(r_i^k\right)^{1-\eta} Q_i^k = r_i^k \sum_{f\in\mathcal{F}_i} s_i^f A_i^{fk} \left(\pi_i^{fk}\right)^{(\theta-1)/\theta}. \tag{27}$$

Under the Armington assumption, a crop k that is produced under the current climate in a country i is always produced in this country under climate change as long as there exists a field $f \in \mathcal{F}_i$ with strictly positive potential yields, $A_i^{fk} > 0$. This is derived from the imperfect substitutability of crops originating from different countries. The assumption of integrated world markets is a different case where nothing prevents the price of a crop from reaching a level inferior to the cost of non-land inputs in country i, A_i^0/A_i^{Nk}, a situation where equation (21) would no longer be valid. To account for this possibility, equation (21) is implemented as a complementary slackness condition:

$$r_i^k \geq 0 \quad \perp \quad \left(r_i^k\right)^{1-\eta} \geq \left(p_i^k\right)^{1-\eta} - \left(A_i^0/A_i^{Nk}\right)^{1-\eta}, \tag{28}$$

which ensures that r_i^k is strictly positive if the price is above the cost of non-land inputs and is null otherwise.

3.3.3 Livestock

Livestock products are produced by combining feed and labor:

$$Q_i^{\mathrm{l}} = \min\left(\frac{x_i}{\mu_i}, \frac{N_i^{\mathrm{l}}}{\nu_i^{\mathrm{l}}}\right), \tag{29}$$

where x_i is the demand for feed, parameter μ_i is the quantity of feed necessary to produce one unit of animal output, N_i^l is the quantity of labor used for production, and ν_i^l is the unit-labor requirement for livestock production.

Animal feed is produced competitively from a combination of the various crops used to feed animals, and takes a CES form:

$$x_i = \left[\sum_{k\in\mathcal{K}^c} \left(\beta_i^{k,\mathrm{feed}}\right)^{1/\varsigma} \left(x_i^k\right)^{(\varsigma-1)/\varsigma}\right]^{\varsigma/(\varsigma-1)}, \tag{30}$$

where $\varsigma > 0$ and $\neq 1$ is the elasticity of substitution among the various feed crops, and $\beta_i^{k,\mathrm{feed}} \geq 0$ is an exogenous technological parameter. For the model version based on the Armington assumption, the bundles of imported and domestic crops used to produce the animal feed, x_i^k, are obtained using the same Armington aggregator used for composite final goods.

From equations (29) and (30), cost minimization in the livestock feed sector implies for $k \in \mathcal{K}^c$:

$$p_i^{\mathrm{l}} = \nu_i^{\mathrm{l}} A_i^0 + \mu_i P_i^{\mathrm{feed}}, \tag{31}$$

$$x_i^k = \beta_i^{k,\mathrm{feed}} \left(\frac{P_i^k}{P_i^{\mathrm{feed}}}\right)^{-\varsigma} \mu_i Q_i^{\mathrm{l}}, \tag{32}$$

$$P_i^{\mathrm{feed}} = \left[\sum_{k\in\mathcal{K}^c} \beta_i^{k,\mathrm{feed}} \left(P_i^k\right)^{1-\varsigma}\right]^{1/(1-\varsigma)}, \tag{33}$$

where P_i^{feed} is the price index corresponding to the demand for the feed bundle $x_i = \mu_i Q_i^l$.

3.4 Market clearing and equilibrium definition

The market equilibrium for goods is given by the equality between the value of production and the export demand from all countries:

$$p_i^k Q_i^k = \sum_{j \in \mathcal{I}} X_{ij}^k. \tag{34}$$

Under the integrated world markets assumption, consumer prices and producer prices are equal,

$$P_i^k = p_i^k = p^k \text{ for all } k \in \mathcal{K}^a, \tag{35}$$

and market clearing takes place in the world market:

$$\sum_{i \in \mathcal{I}} Q_i^k = \sum_{i \in \mathcal{I}} \left[C_i^k + \mathbf{1}_{k \in \mathcal{K}^c} \left(x_i^k \right) \right] \text{ for all } k \in \mathcal{K}^a, \tag{36}$$

except for grass:

$$Q_i^g = x_i^g, \tag{37}$$

although its domestic price is implicitly set by the world price for livestock products through equations (31) and (33).

Based on the above I can define the competitive equilibrium as follows:

Definition 1. A competitive equilibrium under the Armington assumption is a vector of the consumption of the bundle of agricultural goods (C_i), the price of the bundle of agricultural goods (P_i), the final consumption of the agricultural goods (C_i^k), the consumption price (P_i^k), total imports (X_i^k), bilateral exports (X_{ij}^k), price index of land rents (r_i^k), the acreage share (π_i^{fk}), production (Q_i^k), the producer price (p_i^k), demand for feed (x_i^k), and the aggregate feed price (P_i^{feed}) such that equations (10)–(12), (14)–(16), (21), (23), (26), and (31)–(34) hold.

And similarly for the integrated world markets case:

Definition 2. A competitive equilibrium with integrated world markets is a vector of the consumption of the bundle of agricultural goods (C_i), the price of the bundle of agricultural goods (P_i), the final consumption of agricultural goods (C_i^k), the acreage share (π_i^{fk}), production (Q_i^k), the price index of land rents (r_i^k), demand for feed (x_i^k), the aggregate feed price (P_i^{feed}), price (p^k), and the price of grass (p_i^g) such that equations (10)–(12), (23), (26), (28), (31)–(33), and (35)–(37) hold.

3.5 Welfare measures

Below, I introduce three measures of welfare changes following a shock to land productivity, A_i^{fk}, caused by climate change. As in the textbook examples, the counterfactual value of a variable v is denoted v' and its counterpart under the supply-side approach is denoted v^*. I also denote $\hat{v} \equiv v'/v$ as the relative changes in any variable between the baseline and the counterfactual equilibria.

Equivalent variation A theoretically exact measure of welfare change is obtained by calculating the equivalent variation of the representative household. The household expenditure function is

$$e\left(P_j^0, P_j, U_j\right) = P_j^0 U_j + \beta_j \left(P_j^0\right)^{\epsilon} \begin{cases} P_j^{1-\epsilon}/(1-\epsilon) & \text{if } \epsilon \neq 1, \\ [1 - \ln(\beta_j P_j^0 / P_j)] & \text{if } \epsilon = 1, \end{cases} \tag{38}$$

from which the equivalent variation can be obtained. After a few calculations, and neglecting trade deficits which will be removed before the simulations, equivalent variation can be expressed in terms of the variables in relative changes as

$$\Delta W_j = R_j \left(\hat{R}_j - 1\right) - P_j C_j \begin{cases} (\hat{P}_j^{1-\epsilon} - 1)/(1-\epsilon) & \text{if } \epsilon \neq 1, \\ \ln \hat{P}_j & \text{if } \epsilon = 1, \end{cases} \tag{39}$$

where $R_j = \sum_{k \in \mathcal{K}^c} R_j^k$ are total land rents.[10]

Given the model assumptions of quasi-linear utility and a freely traded outside good, the model is a *de facto* partial equilibrium model in which only the prices set in agricultural markets adjust. This allows welfare to be decomposed into two simple terms: producer surplus, $R_j(\hat{R}_j - 1)$, and consumer surplus. This is a useful decomposition given that the supply-side and the production approaches focus on only the producer surplus.

Supply-side approach Under the supply-side approach, welfare change is measured by the change in land rents caused by the productivity change associated with climate change but assuming constant prices:[11]

$$\Delta W_j^* = \sum_{k \in \mathcal{K}^c} R_j^{k^*} - R_j^k. \tag{40}$$

From equation (39), we observe that in this model this is also a valid welfare measure under the assumption of constant prices. If prices are constant, the consumer surplus is constant and drops from equation (39), and changes in land rents are the same as under the supply-side approach.

In this setting, the price index of land rents, r_j^k, remains constant given that it is a function only of crop prices which are assumed to be constant. As a consequence, the supply-side counterfactual share of land planted with crop k will be

$$\pi_j^{f\,k*} = \frac{\left(r_j^k A_j^{f\,k\prime}\right)^\theta}{\sum_{l \in \mathcal{K}^c, r_j^l \geq 0} \left(r_j^l A_j^{f\,l\prime}\right)^\theta}. \tag{41}$$

It follows that the counterfactual land rents under the supply-side approach are

$$R_j^{k^*} = r_j^k \sum_{f \in \mathcal{F}_j} s_j^f A_j^{f\,k\prime} \left(\pi_j^{f\,k*}\right)^{(\theta-1)/\theta}, \tag{42}$$

from which an expression of the welfare changes under the supply-side approach can be derived:

$$\Delta W_j^* = \sum_{f \in \mathcal{F}_j, k \in \mathcal{K}^c} s_j^f r_j^k \left[A_j^{f\,k\prime} \left(\pi_j^{f\,k*}\right)^{(\theta-1)/\theta} - A_j^{f\,k} \left(\pi_j^{f\,k}\right)^{(\theta-1)/\theta} \right]. \tag{43}$$

In this model, the labor demand for crop production is given by $N_i^k = (A_i^{N\,k})^{\eta-1} Q_i^k (p_i^k / w_i)^\eta$. So under the

[10] Equivalent variation is defined by $\Delta W_j = e(P_j^0, P_j, U_j') - e(P_j^0, P_j, U_j) = P_j^0(U_j' - U_j) = U_j' - U_j$. In the case of $\epsilon \neq 1$, replacing utility by its expression and C_j^0 by the household's budget constraint, $C_j^0 = E_j - P_j C_j$ with E_j the country expenditures, gives $U_j = E_j - P_j C_j + \beta_j^{1/\epsilon} C_j^{1-1/\epsilon}/(1-1/\epsilon)$. Note that from the budget constraint equation, $E_j = A_j^0 N_j + R_j + \Delta_j$ and assuming constant or no trade deficits Δ_j, we have $E_j' - E_j = R_j(\hat{R}_j - 1)$. Then replacing C_j' using equation (10) gives $-P_j' C_j' + \beta_j^{1/\epsilon}(C_j')^{1-1/\epsilon}/(1-1/\epsilon) = -P_j C_j \hat{P}_j^{1-\epsilon}/(1-\epsilon)$ and equation (39). The same steps apply if $\epsilon = 1$.

[11] A standard econometric supply-side approach in cross-section would consist of regressing the farmland value per hectare, Y_j^f (in the model $R_j^f(1+\rho)/\rho s_j^f$, where ρ is the discount rate), on a vector of the climate variables, Z_i^f, and some controls, X_i^f: $Y_j^f = Z_f^f b_j + X_j^f a_j + \varepsilon_j^f$. The estimated marginal value of climate $\hat{b}_j$ can then be combined with climate change projections ΔZ_j^f to calculate the impact of climate change. Using this method, the aggregate and annualized effects of climate change at the country-level are given by $\Delta W_j^* = [\rho/(1+\rho)] \sum_{f \in \mathcal{F}_j} s_j^f \Delta Z_j^f \hat{b}_j$.

supply-side approach assumption of constant prices, labor demand evolves proportional to production as if the production function was Leontief and the elasticity of substitution, η, in this approach should not play a role in welfare changes.

Welfare changes under the supply-side approach can be expressed differently: $\Delta W_j^* = (\delta_j^* - 1)R_j$ with

$$\delta_j^* = \frac{\sum_{f \in \mathcal{F}_j, k \in \mathcal{K}^c} s_j^f r_j^k A_j^{fk'} \left(\pi_j^{fk*}\right)^{(\theta-1)/\theta}}{R_j} \tag{44}$$

the size of the country-level shock calculated after acreage adjustments but under constant prices (and using land rents as the weight). Supply-side welfare change is proportional to the initial land rents which determine the potential importance of the country's agricultural sector. δ_j^* is analogous to a shock to the slope of the supply curve in sections 2.1 and 2.2.

Production function approach To ease interpretation of the results, I introduce a third measure of welfare: the production function approach. This approach predates the Ricardian approach and is described by Mendelsohn et al. (1994) as the "dumb farmer scenario". It neglects both price changes and land re-allocations and is derived as follows. First, use of a deterministic or statistical crop model to derive the effect of climate change on yields. Second, combining these yield changes with a measure of the economic importance of each crop to calculate the economic impact of climate change which is considered to be a measure of welfare.[12]

Following this logic I can derive a measure that is consistent with my model. Following the supply-side method, a welfare change in the production function approach is represented by a change in land rents assuming constant acreages:

$$\Delta W_j^\circ = \sum_{f \in \mathcal{F}_j, k \in \mathcal{K}^c} s_j^f r_j^k A_j^{fk} \left(\pi_j^{fk}\right)^{(\theta-1)/\theta} \left(\hat{A}_j^{fk} - 1\right), \tag{45}$$

denoting the production function counterfactual using $\circ$ as an exponent.

There are two things to note about this welfare measure. First, it is the same as the productivity term in a first-order approximation of the market equilibrium welfare changes in equation (39) (see Gouel and Laborde, 2021, Section 3.4); the other term in the decomposition corresponds to the terms of trade. Second, similar to the welfare measure under the supply-side approach, it can be obtained by combining

$$\delta_j = \frac{\sum_{f \in \mathcal{F}_j, k \in \mathcal{K}^c} s_j^f r_j^k A_j^{fk} \left(\pi_j^{fk}\right)^{(\theta-1)/\theta} \hat{A}_j^{fk}}{R_j}, \tag{46}$$

the size of the country-level shock calculated under the assumption of no adjustment (and using land rents as the weight) and total land rents: $\Delta W_j^\circ = (\delta_j - 1)R_j$.

4 Calibration and counterfactual scenario

Since the calibration of the model closely follows Gouel and Laborde (2021), I describe it only briefly here and refer readers to Gouel and Laborde's paper for more details. The information required to calibrate the model is identified by expressing the model in changes relative to the equilibrium under the current climate (Appendix B.1). I separate the required information into the behavioral parameters that define the behavior given the initial equilibrium, and the data that define the initial equilibrium. Behavioral parameter values are taken from the literature. The values and sources of parameters and data are presented in table 3.

[12]To be complete and cover all the approaches used historically to assess the welfare effect of climate change in agriculture, a 4$^{\text{th}}$ measure of welfare could be introduced to represent the measures obtained from the traditional CGE models. These models tends to represent limited within-country heterogeneity and could be mimicked by collapsing all the fields into one field per country. Such a measure is already provided in Table 5 (column 4) in Gouel and Laborde (2021). This shows that neglecting possible within-country re-allocations severely biases the results.

Table 3: Parameterization

Parameter	Economic interpretation	Target/Source
Behavioral parameters		
$\epsilon = 0.5$	Elasticity of food demand	Comin et al. (2021)
$\kappa = 0.6$	Substitution elasticity between food products	Typical food demand elasticity in the literature (Andreyeva et al., 2010; Muhammad et al., 2011; Chen et al., 2016)
$\varsigma = 0.9$	Substitution elasticity between crops for livestock feed	Rude and Meilke (2000)
$\sigma = 5.4$	Armington elasticity	Estimated for the 10 most important crops in Costinot et al. (2016)
$\eta = 0$	Substitution elasticity between land and non-land inputs	Berry and Schlenker (2011)
$\theta = 1.1$	Shape of the Fréchet distribution	Supply elasticity of 0.4 for United States maize and soybean (Miao et al., 2016)
Initial equilibrium		
A_i^{fk}	Land productivity shifter	Potential yields from the GAEZ project (IIASA/FAO, 2021)
$p_i^k Q_i^k$	Value of production	FAOSTAT for crops, except grass, and GTAP 9.2 (Aguiar et al., 2016) for the rest
R_i^k	Land rents	Value of production from FAOSTAT times share of land in production costs from GTAP
X_{ij}^k	Value of imports	FAOSTAT for crops and GTAP for livestock
$P_i^k x_i^k$	Value of feed consumption	FAOSTAT, except for grass taken from GTAP
$P_j^k C_j^k$	Value of consumption	FAOSTAT for crops and GTAP for livestock
r_i^k	Price index characterizing per-hectare land rents	From first-order condition (27) using A_i^{fk} and R_i^k as observables
π_i^{fk}	Land-use shares	From equation (23) after the calculation of r_i^k

4.1 Behavioral parameters

The parameter ϵ determines the elasticity of demand for the food bundle. Based on the estimate in Comin et al. (2021) and the structural change literature more generally, a reasonable value for that elasticity is 0.5.

For the elasticity of substitution between food products, I rely on the literature estimating food demand elasticities. Demand elasticities for food products have been well studied with typical elasticities found to be below 1 in absolute values and between 0.3 and 0.8 (Andreyeva et al., 2010; Muhammad et al., 2011; Chen et al., 2016). Using as a target the typical elasticity proposed in this literature leads to an elasticity of substitution close to 0.6 adopted here. However, most of this literature is concerned with final and not primary goods as in my model. A higher substitution elasticity could be expected between some of the products such as cereals but not among all products given their different nature (e.g., consider cereals, stimulants—cocoa, coffee, and tea—and livestock products).

The literature on feed demand elasticities is small and dated and points to more elastic demand than the demand for food. Based on Rude and Meilke (2000), I calibrate the substitution elasticity among crops for livestock feed, ς, at 0.9.

The Armington elasticity, σ, is taken as equal to 5.4 based on the estimates in Costinot et al. (2016) for the 10 most important crops in the model.

The elasticity η governs the overall supply elasticity of the agricultural sector and is related to the possibility to increase yields by adding more inputs. While there is little question that modern inputs are crucial for achieving current yields, whether use of current inputs and yields react much to price changes is open to question. This empirical issue is at the center of debate on the indirect land use change effect of biofuel policies. Analyzing yield and fertilizer responses to prices, Berry and Schlenker (2011) estimate a yield-price elasticity close to zero. I follow their results and adopt $\eta = 0$. This is obviously the most conservative estimate of this parameter but following the insights in section 2.1 it is an assumption that favors the supply-side approach which also neglects such reactions.

The shape of the Fréchet distribution, θ, is set equal to 1.1 by targeting supply elasticities for United States maize and soybean of 0.4, a frequent value in the literature (Miao et al., 2016). See Gouel and Laborde (2021, Table 3) for more studies related to these elasticities.

4.2 Initial equilibrium

The initial equilibrium is constructed from information on production, consumption, and trade flows in 2011, and potential yields around the turn of the century. I discretize the world into $30' \times 30'$ grid cells, retaining only cells with some agricultural land use in 2011 (Goldewijk et al., 2017). At the equator, the side length of a cell is approximately 56 km. Each cell based on its location is associated to a single country or where relevant split among several countries. This results in 64,858 fields which corresponds to a level of spatial aggregation commonly adopted in supply-side approaches. For example, in the model the United States is composed of 4,768 fields which is a number higher than its number of counties, the level used for most regressions (e.g., Mendelsohn et al., 1994; Schlenker et al., 2005; Deschênes and Greenstone, 2007). The model includes 50 countries, 9 of which correspond to regional aggregates of several countries (see table A1 for details), and 35 crops (table A2) which have available information on both potential yields, supply and use. The crop coverage is sufficiently large to assume use of all agricultural land.

Land productivity shifter Each field is associated to potential yields for all crops. These potential yields are aggregated at the 30-arcminute level from the 5-arcminute information provided by the GAEZ project (IIASA/FAO, 2021). Appendix B.2 shows that the land productivity shifter, A_i^{fk}, can be set equal to the information on potential yields. Potential yields are obtained under high inputs and rain-fed assumptions and are calculated based on the average weather observed between 1981 and 2010.

Market equilibrium Most of the data characterizing the initial market equilibrium are from FAOSTAT, augmented by the GTAP database version 9.2 (Aguiar et al., 2016). GTAP 9.2 provides information base on a 2011 reference year. In the case of the FAOSTAT data, to remove potential outliers I take the average for 2010–2. The value of production for all crops, except grass, is from the FAOSTAT Value of Agricultural Production database. There are missing values in this database, when prices are not available. In the case of missing values I impute prices based on the average world price weighted by the quantities produced, and the value of production is calculated as price multiplied by quantity. The value of production of livestock products is from GTAP. The value of production of grass is also from GTAP and is represented by payments to the land factor by the livestock sectors.

Land rents, R_i^k, are obtained by multiplying the previously obtained value of crop production by the share of land in crop production costs from GTAP.

Trade values for crops are from FAOSTAT, and by default use importer declarations where available. Trade values for livestock products are from GTAP. Both these sources are based on COMTRADE data aggregated at the appropriate product level.

The values of crops used for livestock feed are calculated using FAOSTAT commodity balances which provide information on the various sources of supply (production, imports, and stocks) and the various uses. Using the commodity balance, I can calculate the share of feed in total supply which I multiply by the value of production plus imports, which assumes a common price for production and imports.

The value of consumption is calculated as a residual from the value of production plus imports minus the value of feed and exports.

There are some inconsistencies among sources (e.g., between the trade and the production and use data). The original data are adjusted using a cross-entropy procedure to satisfy a market equilibrium consistent with the model equations.

Initial land allocation The initial land allocation, π_i^{fk}, and the initial price index of land rents, r_i^k, can be recovered from the optimality conditions of the land owner problem and the other observables. For given aggregate land rents

R_i^k and potential yields A_i^{fk}, there is a unique set of r_i^k compatible with equation (27) (see Gouel and Laborde, 2021, Appendix A for the proof). Using the r_i^k, the initial land allocation can be calculated using equation (23).

4.3 Climate change counterfactual

After calibrating the model to replicate the equilibrium under the current climate, current trade imbalances are removed. Given the model structure, this only affects the GDP used to normalize the welfare results but not the equilibrium in the agricultural markets. The model then is used to simulate the effects of climate change on agriculture by changing the value of potential yields to the values provided by the GAEZ project at the 2080s horizon for the climate model HadGEM2-ES under the RCP8.5 greenhouse gas (GHG) concentration scenario which is the most pessimistic scenario, and under the assumption that potential yields benefit from the fertilization effects of CO_2. The new equilibrium is obtained by solving the model equations, expressed as deviations from the benchmark equilibrium in Appendix B.1, using the modeling language GAMS. The model is solved in two steps. First, I identify the sectors where production ends as a result of zero potential yields under climate change. For those sectors, production and land rents are fixed at zero, producer prices are set to infinity, and the other equilibrium values are solved for. Second, all the other changes in potential yields are applied and the equilibrium is solved for.

5 Results

5.1 Main welfare results

This section discusses the main welfare results obtained by solving the model after changing the values of potential yields, A_i^{fk}, from their values under current climate conditions to values under climate change conditions. Table 4 presents the main results. Column 1 reports the net agricultural trade (exports minus imports) value as a share of the value of agricultural production. This measure can be used as a predictor of the direction of the supply-side approach bias related to the terms-of-trade effects. Column 2 reports the share of land rents with respect to GDP. Land rents are an important measure since by construction, the production function and supply-side approaches deliver welfare changes that are proportional to the initial land rents ($\Delta W^\circ = (\delta_j - 1)R_j$ and $\Delta W^* = (\delta_j^* - 1)R_j$). Columns 3 and 4 report $\delta_j - 1$ and $\delta_j^* - 1$, the aggregate change in crop production using land rents as a weight and assuming respectively, no adaptation and adaptation through acreage changes at constant prices. The production function approach welfare change (column 5) is derived by multiplying the results in column 2 by those in column 3, and the supply-side approach welfare change (column 6) is obtained by multiplying the results in column 2 by the results in column 4. Column 7 reports the welfare changes accounting for price changes and column 8 presents the results for the relative bias of the supply-side approach. All welfare changes are expressed as percentages of GDP (with trade deficits removed).

One of the insights provided by Mendelsohn et al. (1994) is that accounting for adaptation through the land market is important because the "dumb farmer" assumption in the production function approach leads to excessive welfare losses. This is confirmed by the results in table 4 column 6 which are always superior to or equal to the results in column 5. This changes if we account for market-mediated adaptation (compare columns 6 and 7). In this case, the bias can go in both directions but on average and more often than not market equilibrium welfare changes are lower than the supply-side changes (for 38 out of 50 countries). A good predictor of the direction of these results is if the country is a net food importer (negative signs in column 1). Almost all net importers have a negative bias. Net exporters with a sufficiently large export surplus that do not experience too large a climate change shock (e.g., Argentina and Brazil) present a positive bias: the exact welfare change exceeds the supply-side change. Consistent with the insights in section 2.2, these results show that terms-of-trade effects are a strong driver of the sign and size of the bias of the supply-side approach at country level.[13]

[13]The importance of the terms-of-trade effect of climate change is emphasized in Gouel and Laborde (2021) and Baldos et al. (2019) among others.

Table 4: Main welfare results

Country[a]	Net ag. trade as % of ag. prod. (1)	Land rents as % of GDP (2)	$\delta_j - 1$ (%) (3)	$\delta_j^* - 1$ (%) (4)	Welfare change (% of GDP) Production fn. (5)	Supply-side (6)	Exact (7)	$\text{Bias}_j / \Delta W_j$ (%) (8)
Argentina	60.64	1.24	16.48	19.26	0.20	0.24	0.58	58.55
Australia	34.77	0.28	−47.23	−45.39	−0.13	−0.13	−0.05	−145.60
Bangladesh	−31.37	3.17	−30.01	−29.22	−0.95	−0.93	−12.42	92.53
Brazil	38.01	0.67	−25.99	−24.43	−0.17	−0.16	0.44	136.75
Canada	25.36	0.16	18.89	52.93	0.03	0.08	−0.04	295.02
China (including Hong Kong)	−4.92	1.95	21.95	48.89	0.43	0.95	0.22	−327.01
Colombia	4.46	1.24	−34.59	−32.03	−0.43	−0.40	−1.05	62.22
Egypt	−67.51	0.31	−79.76	−58.87	−0.25	−0.18	−2.97	93.82
Ethiopia	0.70	4.80	52.89	65.26	2.54	3.13	0.11	−2699.11
France	17.59	0.19	−5.24	−4.08	−0.01	−0.01	0.05	114.83
Germany	−7.36	0.16	10.59	11.33	0.02	0.02	−0.19	109.56
Greece	−9.58	0.81	1.73	6.05	0.01	0.05	−0.33	114.88
India	4.81	4.72	−17.93	−15.72	−0.85	−0.74	−6.35	88.32
Indonesia	−7.78	4.94	−22.90	−21.74	−1.13	−1.07	−3.97	72.98
Iran	−15.04	0.42	73.56	124.67	0.31	0.52	0.59	12.29
Italy	−23.46	0.22	−2.62	7.89	−0.01	0.02	−0.28	106.13
Japan	−31.64	0.18	38.83	59.67	0.07	0.11	−0.04	356.31
Kazakhstan	−1.14	0.61	34.17	66.04	0.21	0.40	−0.32	228.00
Kenya	4.85	1.29	3.66	12.31	0.05	0.16	4.24	96.25
Korea, South	−49.81	0.52	54.24	55.86	0.28	0.29	−0.14	307.97
Malaysia	−30.05	2.72	−5.67	−5.54	−0.15	−0.15	−2.29	93.41
Mexico	−18.08	0.46	−14.42	−9.09	−0.07	−0.04	−0.12	64.63
Morocco	−26.88	0.82	−87.86	−87.44	−0.72	−0.71	−8.85	91.94
Netherlands	−16.22	0.12	20.36	21.08	0.02	0.02	−0.73	103.37
Nigeria	−9.83	1.38	−27.27	−26.02	−0.38	−0.36	−8.79	95.92
Pakistan	1.86	3.07	−24.24	−20.84	−0.74	−0.64	−2.67	75.99
Peru	−5.98	1.39	91.26	209.16	1.27	2.91	0.96	−201.61
Philippines	−0.77	3.20	−16.26	−15.69	−0.52	−0.50	−0.36	−40.71
Poland	2.30	0.84	−2.25	60.54	−0.02	0.51	−0.20	353.54
Romania	−2.06	1.82	−18.06	−17.86	−0.33	−0.33	−0.62	47.71
Russia	−8.84	0.54	0.94	6.22	0.01	0.03	−0.19	117.43
Senegal	−45.00	1.23	−66.38	−65.00	−0.82	−0.80	−7.99	90.00
South Africa	1.42	0.21	−10.14	−5.71	−0.02	−0.01	−0.12	89.58
Spain	1.73	0.20	−32.49	−25.77	−0.07	−0.05	−0.06	10.42
Sri Lanka	−38.03	1.94	−30.30	−29.38	−0.59	−0.57	−3.99	85.71
Thailand	20.42	2.52	−44.63	−43.56	−1.12	−1.10	−2.23	50.69
Turkey	−7.16	0.48	38.73	53.61	0.19	0.26	−0.08	439.99
Ukraine	30.74	1.82	−21.70	−21.50	−0.39	−0.39	−0.12	−230.14
United Kingdom	−38.08	0.14	32.04	34.43	0.05	0.05	−0.14	134.25
United States	15.37	0.26	−4.96	6.35	−0.01	0.02	−0.03	150.31
Viet Nam	−1.80	6.56	−19.39	−17.55	−1.27	−1.15	−1.57	26.74
Asia	−5.92	1.82	0.22	13.34	0.00	0.24	−0.92	126.56
CIS[b]	−1.49	0.77	7.83	30.27	0.06	0.23	−0.24	198.53
Europe	−5.18	0.25	−0.54	11.34	−0.00	0.03	−0.18	116.29
Latin America	23.68	0.81	−15.71	−7.39	−0.13	−0.06	0.17	135.61
Middle East and North Africa	−39.36	0.29	12.05	30.30	0.03	0.09	−0.76	111.37
Northern America	16.58	0.25	−3.42	9.36	−0.01	0.02	−0.03	169.03
Oceania	37.33	0.35	−31.37	−25.53	−0.11	−0.09	−0.01	−598.01
Sub-Saharan Africa	−3.06	1.39	−22.82	−19.87	−0.32	−0.28	−4.20	93.44
World	0	0.78	−2.15	10.40	−0.02	0.08	−0.43	118.76

Notes: Columns 3 and 4 represent the aggregate change in crop production using land rents as weight and assuming, respectively, no adaptation and adaptation through acreage changes at constant prices. Columns 5 and 6 can be obtained by multiplying column 2 by, respectively, columns 3 and 4.
[a] Only countries represented individually in the model are presented here. [b] Commonwealth of Independent States.

Terms-of-trade effects cancel out at the world level but the bias remain: the global welfare change accounting for price changes is a welfare loss of 0.43% while the supply-side approach welfare change is a 0.08% gain. As predicted by the example in section 2.3, in the absence of terms-of-trade effects and when the bias is caused by the imperfect substitutability of crops, the market equilibrium welfare should be inferior to the supply-side welfare, a situation confirmed at the world level for all the parameter variations considered in the paper.

The welfare changes under the supply-side approach are superior to the welfare changes under the production function approach but tend to be of the same order of magnitude because they are proportional to the initial land rents. Their welfare values are obtained by multiplying the initial land rents by the indexes of production change (δ_j and δ_j^*); thus the values of these indexes explain the differences between the results in columns 5 and 6. Since the only difference between columns 3 and 4 is the acreage adjustments incentivized by relative yield changes, these differences are due to the between-crop heterogeneity of the climate shock. If the shock is uniform across crops, acreages do not adjust and $\delta_j = \delta_j^*$ which applies to many countries. However, a few countries show sizable differences. It can be observed also that compared to the welfare change accounting for price changes the welfare changes under the supply-side and production function approaches are of a different order of magnitude because they cannot account for the possibility that food may become scarcer under climate change which would make land more valuable and raise land rents. This explains the size of the relative bias in column 8 which generally takes values around 100; where they exceed 100 this indicates a different sign for the welfare changes under the supply-side and market equilibrium approaches.

Accounting for price changes, some countries achieve gains from climate change. This can happen under two settings: a country that benefits from climate change under the production function and supply-side approaches or a country that benefits from improved terms of trade, typically an exporting country. These two effects can be combined and become mutually reinforcing. For example, Argentina benefits from higher yields under climate change but is also an important exporter and benefits from higher export prices. Brazil and France show negative welfare changes under the supply-side approach but positive market equilibrium welfare changes which means that in their case terms-of-trade effects likely dominate productivity effects. For net importers the reverse applies—welfare gains under the supply-side approach but negative market equilibrium welfare changes (e.g., Germany, Greece, and Japan). In these cases, the gains from higher yields are compensated by losses due to higher import prices.

A landmark debate in the early supply-side literature focuses on whether the United States would benefit from global warming (Mendelsohn et al., 1994; Schlenker et al., 2005; Deschênes and Greenstone, 2007). In table 4, under the supply-side approach the United States benefits slightly but suffers slightly under the equilibrium approach. The sign of the supply-side welfare change is robust to the parameter choice; it does not change across all the specifications tested below. However, it is slightly dependent on the climate scenario. In section 6.2, I compare 40 climate scenarios and in 3, the United States suffers from climate change under the supply-side approach. The result that the United States loses from climate change under the equilibrium approach is also quite robust.[14] Welfare gains occur only for the limited combination of parameters under which the bias of the supply-side approach is low and for 9 out of the 40 climate scenarios analyzed. In the United States case, its net-export position is not enough for the terms of trade to offset the costs of climate change.

5.2 Validity conditions of the supply-side approach

This section explores the combinations of assumptions that allow the supply-side approach to provide an unbiased approximation of the market equilibrium welfare changes. Figure 4 presents scatter plots of the welfare changes under the supply-side approach with respect to the market equilibrium welfare changes for the 50 countries in the model, and for the world (the red triangle). Countries which show opposite signs for the welfare results under the two methods are colored pink. Each panel corresponds to a different set of model assumptions and reports a linear regression, its R-squared, and the regression line (colored in blue). Panel 1 provides a graphic representation of the results in table 4.

For all the model assumptions considered here and in appendix welfare changes under the supply-side approach are positively correlated to the market equilibrium welfare changes but the correlations are high only for particular

[14] A result found in other works based on equilibrium models, e.g. Costinot et al. (2016), Baldos et al. (2019), and Gouel and Laborde (2021).

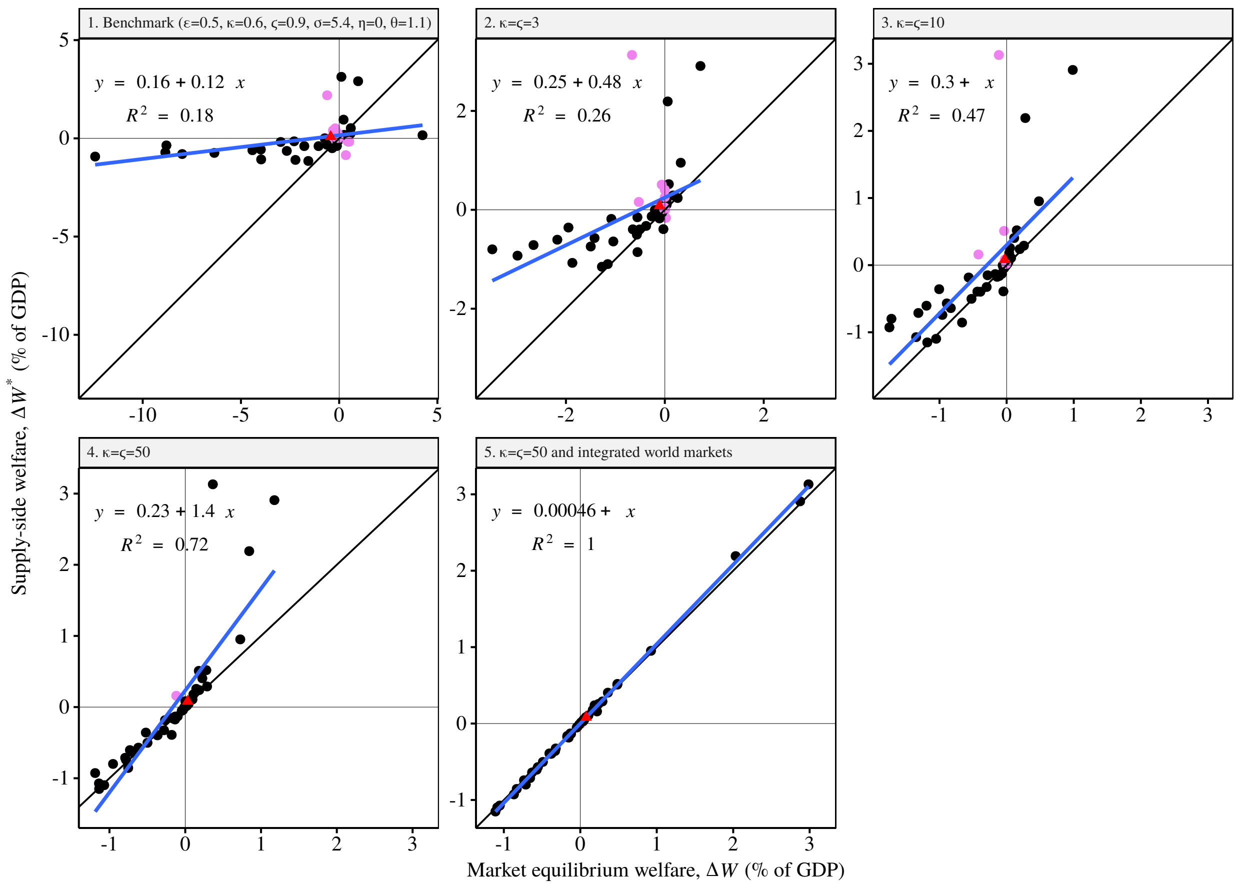


Figure 4: The role of demand substitution and trade costs in the bias of the supply-side approach. Notes: pink points indicate countries whose welfare measures have opposite signs, the red triangles are world welfare, and the blue lines are the regression lines which are displayed also as equations in the top-left part of each panel. With the exception of panel 1, panel titles correspond to the assumptions and parameters that have changed, with the remaining assumptions and parameters as in the benchmark situation.

parameter combinations. Welfare changes under the supply-side approach are also mostly located above the diagonal lines indicating underestimation of the welfare cost of climate change. The key parameters governing the bias of the supply-side approach are the elasticities of substitution for final and intermediate demand, κ and ς. Panels 2, 3, and 4 increase these elasticities to 3, 10, and 50, with all other parameters at their benchmark values. Higher values for κ and ς increase the R^2 from 0.18 in the benchmark case to 0.26, 0.47, and 0.72 for the respective elasticities values of 3, 10, and 50. For elasticities of 10, the fit is high but far from perfect for a few countries whose welfare measures differ widely depending on the approach. To obtain a perfect fit among the approaches requires very high elasticity values as in panel 4 but also the assumption of integrated world markets for agricultural products except grass (panel 5). This assumption implies neglect of trade costs and the imperfect substitution by country of origin in the Armington assumption.

The role of κ can be explained easily from equation (39) and is similar to what is illustrated in the example in section 2.3. Consumer surplus is a function of the change in the price of the bundle of agricultural products, $\hat{P}_j$, which itself is a CES price index of import prices with elasticity κ. If the climate change shock is sufficiently heterogeneous among crops, which the difference between δ and δ^* at the world level indicates, then if crops are sufficiently substitutable on the demand side decreased yield from one crop can be compensated by increased yield from another crop. Since from a supply-side perspective, the climate change shock is a small positive shock at the world level ($\delta^*_{\text{World}} = 0.08$), with a high enough κ, $\hat{P}_j$ will be very close to 1, and especially if trade costs are neglected. For $\hat{P}_j = 1$, there are no changes in the consumer surplus caused of climate change, and since relative prices barely change, the supply-side approach provides a good approximation of the changes in land rents. So, following the intuitions in section 2, the supply-side approach has a lowest bias when the climate change shock is uniform across crops, or equivalently if crops are perfectly substitutable.

Note that there is very little evidence on long-run food demand elasticities, which are the elasticities of interest here, but the diversity of local diets could point toward important substitutability (probably linked to slowly evolving consumption habits as in Atkin, 2013). However, while long-run substitution could be high within food groups (e.g., among staple crops, wheat could be replaced by maize or rice), between food groups (starchy staples, vegetables and fruits, oils and fats, and sources of proteins) given their different physiological roles a complementarity relation is more likely. This would suggest being conservatism regarding substitution elasticities which are unlikely to be as high as would be required to obtain a strong correlation between the two welfare measures.

6 Sensitivity analysis

This sensitivity analysis addresses three potential concerns related to the previous results. First, that the model calibration could be biased against the supply-side approach. Second, that the chosen climate scenario could be peculiar in predicting yield shocks that are especially heterogeneous across crops and countries. Third, that the supply-side approach might be better suited to evaluating marginal shocks.

6.1 Model calibration

6.1.1 Results using Costinot et al.'s (2016) parameters

As shown in section 5, the bias of the supply-side approach is a function of the corresponding equilibrium model calibration. Therefore, here I analyze the results for a completely different calibration based on the parameters adopted in Costinot et al. (2016). My model is close to Costinot et al.'s model but differs in its broader coverage of crops, presence of livestock, and absence of an extensive land margin. Also their model is calibrated using parameters which imply more flexible demand and supply (see Gouel and Laborde, 2021, for a discussion of this parameterization). The only parameter that cannot be directly mapped onto Costinot et al.'s parameters is θ, because it does not lead to the same supply elasticities. So, to replicate the behavior of Costinot et al.'s model, I set $\theta = 1.239$ which allows my model to reproduce their average supply elasticity on their set of crops. For the other parameters, I follow Costinot et al. and use $\epsilon = 1$ and $\kappa = \varsigma = 2.82$. Trade and labor-land substitution elasticities are unchanged. Following Costinot et al.'s calibration, crops are much more substitutable on the demand side (more than four times more) and on the supply side (more than two times more), and aggregate food demand is more elastic.

Appendix table A3 presents the results of this calibration which are presented graphically in figure A1, panel 6. Under this more elastic calibration, climate change is less costly on average: the equivalent variation increases from −0.43% to −0.09%. Climate change is more beneficial under the supply-side approach, because the larger supply-side substitution allows for more reallocation toward those crops affected positively by climate change. Since this effect is smaller than the change in the equivalent variation, in this calibration the bias tends to decrease (in absolute value not in percentage value). However, this reduction does not remove the issues identified above: there are several countries that still show the wrong welfare signs, and the correlation between the two welfare measures is low since the R^2 increases only to 0.3. Overall, adopting the more elastic calibration of Costinot et al. (2016) does not affect the previous conclusions.

6.1.2 Intensive margin

The main results are derived under the assumption of no possibility of intensification which is an extreme assumption given the effect of modern inputs on crop production (Farrokhi and Pellegrina, 2021). Table 5 shows the consequences of removing this assumption. Intensification is governed by η the elasticity of substitution between land and labor. For η equal to 0.05, 0.1, 0.2, and 1, the elasticity of the maize yield to price in the United States is 0.24, 0.48, 0.96, and 4.8. Starting from the benchmark calibration, increasing the yield elasticity decreases the global cost of climate change because it adds one margin of adjustment, and for $\eta = 1$, climate change even becomes beneficial. This assumption barely affects the supply-side approach (below the number of digits in table 5). According to equation (43), this assumption should have no effect on the supply-side approach. η affects supply-side results only through the fact that the initial land allocation, π_i^{fk}, is contingent on this parameter value.

Table 5: Results with intensive margin

	Global welfare change (% of GDP)		R^2 of
Model	Supply-side	Exact	$\Delta W^* \sim \Delta W$
Benchmark ($\kappa = 0.6, \varsigma = 0.9, \eta = 0$)	0.08	−0.43	0.18
$\eta = 0.05$	0.08	−0.34	0.18
$\eta = 0.1$	0.08	−0.26	0.17
$\eta = 0.2$	0.08	−0.14	0.13
$\eta = 1$	0.08	0.17	0.04
$\kappa = \varsigma = 50$	0.08	0.03	0.72
$\kappa = \varsigma = 50, \eta = 0.05$	0.08	0.03	0.77
$\kappa = \varsigma = 50, \eta = 1$	0.08	0.03	0.84

Intensification has two opposite effects on the bias of the supply-side approach. On the one hand, intensification makes crop production more responsive to prices changes which cannot be captured by the supply-side approach because it uses constant prices. This effect tends to increase the bias which is presented in the first five rows in table 5 which show that the R^2 decreases. On the other hand, intensification by allowing substitution of land by labor decreases food scarcity and dampens the increase in the food price index which limits the importance of terms of trade effects. The last three rows in table 5 represent situations with large substitution between crops on the demand side ($\kappa = \varsigma = 50$) that is, situations where the relative price changes are much more limited than in the benchmark. In this case, the dampening of the terms of trade dominates and allowing intensification increases the R^2.

This shows that outside extreme calibrations with limited relative price changes, the assumption of no intensification biased the results in favor of the supply-side approach.

6.1.3 Role of the other parameters

Here I analyze the role of assumptions not previously discussed: flexibility of land reallocation, flexibility of trade, elasticity demand for the food bundle. Appendix figure A1 presents scatter plots of the welfare changes under the supply-side approach with respect to the market equilibrium welfare changes for various combinations of assumptions.

The effect of more flexible land reallocation is analyzed in panels 7 and 8, where θ takes values 1.2 and 2. The supply elasticity is proportional to $\theta - 1$ which implies a multiplication by 2 and 10 of the respective supply elasticities. Increasing the supply elasticity decreases the range of welfare changes without affecting the fit of supply-side welfare on exact welfare. This is consistent with the example in section 2.3 where this parameter plays a secondary role.

The role of the trade flexibility is analyzed in panels 9 and 10. In panel 9, the Armington elasticity is increased to 10 which is almost double its benchmark value. In panel 10, the model is simulated under the assumption of integrated world markets. Both assumptions have equivalent effects on the fit and increase it marginally. So, while the assumption of integrated world markets in section 5.2 is crucial to obtain a perfect fit, it matters only if it occurs in combination with high substitution elasticities.

The role of the demand elasticity for the food bundle is analyzed in panels 11 to 13. Given that the supply-side approach neglects changes in consumer surplus and since in equation (39) the consumer surplus is a function of ϵ, this parameter might be expected to play a big role in the bias of the supply-side approach. If we follow the structural change literature (e.g., Comin et al., 2021) and consider 1 an upper bound of this parameter—above 1 the budget share of food decreases as its price increases—then its role is more nuanced. By construction, ϵ does not affect the supply-side welfare measure but does affect the market equilibrium welfare measure by scaling the size of the price increase for the agricultural goods bundle. Therefore, it affects the order of magnitude of the welfare changes. If $\epsilon = 1$, the budget share of the agricultural product is constant at constant income, so at constant income the level of land rents should be similar in magnitude to the benchmark. If $\epsilon < 1$, the budget share of agricultural products and the magnitude of the effect of climate change increase with agricultural prices. However, even though increasing ϵ toward 1 brings the two welfare measures to the same order of magnitudes, figure A1 panel 12 shows that the correlation between these welfare measures is only weakly affected by the increase. ϵ plays a mediating role which increases the effect of κ: a higher ϵ reduces the bias for a given κ but an increase only in ϵ cannot suppress the bias in the same way as increasing κ does.

6.2 Climate scenario

In the paper so far, I consider only one scenario of yield under climate change. Since the bias of the supply-side approach is dependent on the heterogeneity of the shock among crops and countries, it is important to test whether the results hold under different scenarios. For a 2080s horizon, the GAEZ project proposes different scenarios based on choice of GHG concentration (RCP), climate model choice, and choice to account or not for CO_2 fertilization effects in the calculation of yields. Table 6 analyzes all these possible combinations.[15] The results vary widely depending on the scenario. Consistent with expectations, the impact of climate change is higher for higher GHG concentrations and if the CO_2 fertilization effect is ignored. There are also important differences between climate models: IPSL-CM5A-LR leads to the most pessimistic predictions while HadGEM2-ES which is used as the benchmark is close to the average.

While the welfare results vary a lot across scenarios, these variations do not affect my main argument. At world level, there is always an important supply-side approach bias. The low R^2 from regressing supply-side welfare on market equilibrium welfare confirm that the bias is also important at the country level. So, while the chosen benchmark scenario affects the welfare results, it is not the main driver of the importance of the bias of the supply-side approach.

6.3 A marginal climate change shock

Supply-side approaches are designed to measure the marginal value of climate on the agricultural sector although their estimation results are often applied to non-marginal climate scenarios. Here, I analyze the bias in the case of a marginal climate shock. This is implemented in the model by changing potential yields by ν% of the benchmark shock, ν takes the value 100 in the benchmark and takes the values 1 and 0.1 for simulations with two smaller shocks. Table 7 reports the results under the two trade assumptions, Armington and integrated world market.

Table 7 shows that at the global level the bias decreases with the size of the shock and disappears for a marginal shock of 0.1% of the benchmark shock. For a marginal shock, the relative price changes can be neglected making a supply-side approach unbiased at the global level. However, the terms-of-trade effects are still present even for a marginal shock. This is shown in the last column of table 7 which presents the R^2 of regressing the supply-side welfare on the market equilibrium welfare. Decreasing the size of the yield shock increases the R^2 but they remain far from 1, indicating that at the country-level, supply-side and exact welfare are still quite different. The last three rows in table 7 show the effects of marginal shocks under the integrated-world-market assumption: the relative price changes are more

[15] Grass potential yields are available only under the assumption of CO_2 fertilization.

Table 6: Results for different climate scenarios

Climate model	RCP scenario	Without CO_2 fertilization: Global welfare ch. (% of GDP) Supply-side	Without CO_2 fertilization: Global welfare ch. (% of GDP) Exact	Without CO_2 fertilization: R^2 of $\Delta W^* \sim \Delta W$	With CO_2 fertilization: Global welfare ch. (% of GDP) Supply-side	With CO_2 fertilization: Global welfare ch. (% of GDP) Exact	With CO_2 fertilization: R^2 of $\Delta W^* \sim \Delta W$
GFDL-ESM2M	2.6	0.04	−0.02	0.08	0.06	0.00	0.10
GFDL-ESM2M	4.5	0.03	−0.05	0.20	0.08	−0.01	0.17
GFDL-ESM2M	6.0	0.00	−0.13	0.31	0.07	−0.06	0.28
GFDL-ESM2M	8.5	−0.01	−0.38	0.02	0.09	−0.21	0.03
HadGEM2-ES	2.6	0.09	0.01	0.07	0.11	0.02	0.07
HadGEM2-ES	4.5	0.04	−0.13	0.13	0.09	−0.07	0.10
HadGEM2-ES	6.0	0.02	−0.16	0.06	0.09	−0.08	0.03
HadGEM2-ES	8.5	−0.01	−0.66	0.24	0.08	−0.43	0.18
IPSL-CM5A-LR	2.6	0.05	−0.02	0.11	0.07	−0.01	0.09
IPSL-CM5A-LR	4.5	0.01	−0.54	0.38	0.06	−0.47	0.37
IPSL-CM5A-LR	6.0	−0.02	−0.24	0.18	0.05	−0.14	0.09
IPSL-CM5A-LR	8.5	−0.09	−0.97	0.22	0.00	−0.65	0.17
MIROC-ESM-CHEM	2.6	0.07	−0.01	0.09	0.09	0.01	0.11
MIROC-ESM-CHEM	4.5	0.08	−0.06	0.10	0.12	−0.02	0.09
MIROC-ESM-CHEM	6.0	0.02	−0.20	0.12	0.07	−0.29	0.05
MIROC-ESM-CHEM	8.5	−0.01	−0.61	0.22	0.09	−0.38	0.18
NorESM1-M	2.6	0.06	0.02	0.09	0.08	0.03	0.06
NorESM1-M	4.5	0.06	0.00	0.02	0.11	0.03	0.05
NorESM1-M	6.0	0.04	−0.07	0.04	0.12	0.02	0.04
NorESM1-M	8.5	0.00	−0.27	0.08	0.10	−0.12	0.05

Table 7: Results for marginal shocks

Trade assumption	Share of yield shock (%)	Global welfare change (% of GDP): Supply-side	Global welfare change (% of GDP): Exact	R^2 of $\Delta W^* \sim \Delta W$
Armington	100.0	8.1×10^{-2}	-4.3×10^{-1}	0.18
Armington	1.0	4.3×10^{-4}	3.5×10^{-4}	0.48
Armington	0.1	3.1×10^{-5}	3.1×10^{-5}	0.53
Integrated world market	100.0	8.1×10^{-2}	-2.1×10^{-2}	0.20
Integrated world market	1.0	4.3×10^{-4}	4.2×10^{-4}	0.74
Integrated world market	0.1	3.1×10^{-5}	3.1×10^{-5}	0.73

limited in this case, so the bias decreases with the size of the shock more rapidly than with Armington. However, despite a higher R^2, it remains different from 1 with large biases at country level.

These results are consistent with the textbook examples in section 2. The single-country and two-crop model biases would converge to 0 for marginal shocks (i.e., for δ and $\delta_k \to 1$).[16] However, the two-country model biases would converge to non-zero values,[17] a result similar to the standard result from a perfect competition model that a small tariff necessarily raises welfare in a large country due to non-zero terms-of-trade changes (e.g., Feenstra, 2016, Ch. 8). These simulations lead to the conclusion that although supply-side approaches appear to be unbiased for marginal shocks at the global level, this does not apply at the country level because the terms-of-trade changes do not vanish for marginal shocks.

[16] Using L'Hôspital's rule to obtain the limit for equation (7).

[17] With $\lim_{\delta \to 1} \text{Bias}_h / \Delta W_h = -2\eta x_h / (\epsilon - 2\eta x_h + \eta)$ and $\lim_{\delta \to 1} \text{Bias}_f / \Delta W_f = 2\eta m_f / (\epsilon + 2\eta m_f + \eta)$.

7 Conclusions

One of the important advantages of econometric supply-side approaches used to evaluate the economic impact of climate change on agriculture is their simplicity. There is no need to combine the projections of crop scientists related to the effects of climate change on crop yields in an equilibrium model of global agricultural markets and to estimate the model's key parameters. However, I have shown that this simplicity comes at an important cost since it involves several biases. Since they involve reduced-form econometric estimations of how farmland rents or profits evolve with climate, they focus on adaptation at the farm level but neglect the equilibrium in the crop market at the domestic and international levels.

Using simple textbook examples, I have shown that on average a supply-side approach, because it neglects the imperfect substitutability of crops in demand, will underestimate the true welfare losses from climate change, and possibly by a large amount. In addition, by neglecting transfers between countries created by terms-of-trade changes, the supply-side approach could overestimate the losses from climate change for net food exporting countries which may benefit from higher export prices. I confirmed these findings using a parsimonious quantitative trade model of global agricultural markets which takes account of these various mechanisms, imitates the findings of the supply-side approach, and calculates the welfare changes that account for price changes. Comparing both welfare measures shows that under calibrations consistent with the literature, they show a small correlation and potentially different signs. The supply-side approach provides a good approximation of the welfare cost of climate change only if crops are almost perfectly substitutable in demand and if trade costs are neglected, a situation where it is reasonable to assume constant prices as in the supply-side approach.

Supply-side approaches can be biased if used to assess the welfare impact of climate change on agriculture but they have other uses such as understanding the adaptation margins in agriculture. The measurement of adaptation possibilities provides opportunities for interactions between the supply-side and equilibrium literatures. Supply-side approaches measure the marginal effect of climate on land rents or farm profits at constant prices accounting for adaptations at farm-level. This measure could be used to calibrate equilibrium models to ensure that for a marginal shock their supply side reproduces the same moments as supply-side econometric models. Equilibrium models would then be consistent with the econometric evidence for marginal shocks while providing the advantage of nonlinear behavior when analyzing the effects of large climate shocks.

Appendix

A Derivation of bias for the two-crop model

Standard CES algebra gives the compensated demand function,

$$C^k = \beta^k \frac{\left(p^k\right)^{-\kappa}}{\left[\sum_{l=1}^{2} \beta^l \left(p^l\right)^{1-\kappa}\right]^{-\kappa/(1-\kappa)}} U, \tag{A1}$$

and the supply function,

$$Q^k = A^k \frac{\left(p^k A^k\right)^{\theta-1}}{\left[\sum_{l=1}^{2} \left(p^l A^l\right)^{\theta}\right]^{(\theta-1)/\theta}} L. \tag{A2}$$

Taking the ratio of consumption of crop 1 with respect to crop 2 and using market clearing, we obtain the ratio of prices:

$$\frac{p^2}{p^1} = \left[\frac{\beta^1}{\beta^2}\left(\frac{A^2}{A^1}\right)^{\theta}\right]^{1/(1-\kappa-\theta)}. \tag{A3}$$

Normalizing all benchmark prices including price indexes to 1, consumption and productivity shifters can be related to the initial budget shares, α^k:

$$\beta^k = \alpha^k \text{ and } A^k = \left(\alpha^k\right)^{1/\theta}. \tag{A4}$$

Welfare changes under the supply-side approach are given by the changes in land rents at constant prices which, in this setting where land is the only input, is the same as the changes in the value of production:

$$\Delta W^* = \sum_{k=1}^{2} p^k \left(Q^{k*} - Q^k\right). \tag{A5}$$

Taking the initial prices as 1 gives

$$\Delta W^* = \sum_{k=1}^{2} Q^{k*} - L. \tag{A6}$$

Production under the supply-side approach is given by equation (A2) with productivities under climate change conditions, $A^{k\prime}$ but prices under current climate conditions:

$$\Delta W^* = L\left\{\sum_{k=1}^{2} \frac{\left(A^{k\prime}\right)^{\theta}}{\left[\sum_{l=1}^{2} \left(A^{l\prime}\right)^{\theta}\right]^{(\theta-1)/\theta}} - 1\right\}, \tag{A7}$$

$$= L\left\{\left[\sum_{k=1}^{2} \alpha^k \left(\delta^k\right)^{\theta}\right]^{1/\theta} - 1\right\}, \tag{A8}$$

To calculate the true welfare changes from climate change, I first define the counterfactual relative prices from equation (A3) (assuming crop 1 is the numeraire) as

$$p^{2\prime} = \left(\frac{\delta^2}{\delta^1}\right)^{\theta/(1-\kappa-\theta)}, \tag{A9}$$

from which the counterfactual quantities can be derived:

$$Q^{k\prime} = \frac{\alpha^k \left(\delta^k\right)^{-\kappa\theta/(1-\kappa-\theta)}}{\left[\sum_{l=1}^{2} \alpha^l \left(\delta^l\right)^{\theta(1-\kappa)/(1-\kappa-\theta)}\right]^{(\theta-1)/\theta}} L, \tag{A10}$$

Counterfactual utility is given by

$$U' = \left[\sum_{k=1}^{2} \left(\alpha^k\right)^{1/\kappa} \left(Q^{k\prime}\right)^{(\kappa-1)/\kappa}\right]^{\kappa/(\kappa-1)}, \tag{A11}$$

$$= \left[\sum_{k=1}^{2} \alpha^k \left(\delta^k\right)^{1/[1/\theta+1/(\kappa-1)]}\right]^{1/\theta+1/(\kappa-1)} L. \tag{A12}$$

Using that $\Delta W = U' - L$ gives equation (7).

B Further details on calibration

B.1 Equilibrium in relative changes

In this appendix, I express the model equations in relative changes. This form makes explicit the data required for the calibration. I consider one source of exogenous shocks: changes in the parameter governing crop yields, A_i^{fk}. To express the equations in relative changes, I introduce share parameters. $\alpha_j^k = P_j^k C_j^k / P_j C_j$ is the budget share of product k in the consumption of all agricultural goods. $\alpha_j^{k,\text{feed}} = P_j^k x_j^k / P_j^{\text{feed}} x_j$ is the budget share of crop k in livestock feed. $\alpha_{ij}^k = X_{ij}^k / X_j^k$ is the bilateral trade share. $\phi_i^{k,\text{labor}}$, $\phi_i^{k,\text{land}}$, and $\phi_i^{k,\text{feed}}$ are the budget shares of each input of production: labor, land, and feed.

Three variables, A_i^{fk}, π_i^{fk} and Q_i^k, are not fully expressed in relative deviations to allow for the possibility of regime changes: that fields may have zero potential yields in some crops under current climate conditions but positive yields under projected climate change conditions, a situation where $\hat{\pi}_i^{fk}$ and $\hat{A}_i^{fk}$ would not be defined. So, counterfactual acreage shares are expressed as

$$\pi_i^{fk\prime} = \frac{\left(r_i^k \hat{r}_i^k A_i^{fk\prime}\right)^\theta}{\sum_{l\in\mathcal{K}^c} \left(r_i^l \hat{r}_i^l A_i^{fl\prime}\right)^\theta}. \tag{A13}$$

Country-level crop production can be expressed in relative deviations, because it is not possible in the model to start producing a crop in the future if it was not produced under the current climate (since in this case r_i^k would not be defined), but its expression depends on the counterfactual values of A_i^{fk} and π_i^{fk}:

$$\hat{Q}_i^k = \left(\frac{\hat{r}_i^k}{\hat{p}_i^k}\right)^\eta \frac{\sum_{f\in\mathcal{F}_i} s_i^f A_i^{fk\prime} \left(\pi_i^{fk\prime}\right)^{(\theta-1)/\theta}}{\sum_{f\in\mathcal{F}_i} s_i^f A_i^{fk} \left(\pi_i^{fk}\right)^{(\theta-1)/\theta}} \text{ for all } k \in \mathcal{K}^c. \tag{A14}$$

All the other equations follow simply from their expression in levels and if not otherwise specified, the following equations hold for all $i, j \in \mathcal{I}$, $k \in \mathcal{K}$:

$$\hat{P}_j = \left[\sum_{k\in\mathcal{K}^a} \alpha_j^k \left(\hat{P}_j^k\right)^{1-\kappa}\right]^{1/(1-\kappa)}, \tag{A15}$$

$$\hat{C}_j^k = \left(\hat{P}_j^k\right)^{-\kappa} \left(\hat{P}_j\right)^{\kappa-\epsilon} \text{ for all } k \in \mathcal{K}^a, \tag{A16}$$

$$\hat{x}_j^k = \left(\hat{P}_j^k / \hat{P}_j^{\text{feed}}\right)^{-\varsigma} \hat{Q}_j^l \text{ for all } k \in \mathcal{K}^c, \tag{A17}$$

$$\hat{P}_j^{\text{feed}} = \left[\sum_{k \in \mathcal{K}^c} \alpha_j^{k,\text{feed}} \left(\hat{P}_j^k\right)^{1-\varsigma}\right]^{1/(1-\varsigma)}, \tag{A18}$$

$$\begin{cases} \hat{r}_i^k \geq 0 \quad \perp \quad \left(\hat{r}_i^k\right)^{1-\eta} \geq \left[\left(\hat{p}_i^k\right)^{1-\eta} - \phi_i^{k,\text{labor}}\right] / \phi_i^{k,\text{land}} & \text{if } \eta \neq 1, \\ \hat{r}_i^k = \left(\hat{p}_i^k\right)^{1/\phi_i^{k,\text{land}}} & \text{if } \eta = 1, \end{cases} \text{ for all } k \in \mathcal{K}^c, \tag{A19}$$

$$\hat{p}_i^l = \phi_i^{l,\text{labor}} + \phi_i^{l,\text{feed}} \hat{P}_i^{\text{feed}}. \tag{A20}$$

The model using the Armington assumption includes the following equations:

$$\hat{P}_j^k = \left[\sum_{i \in \mathcal{I}} \alpha_{ij}^k \left(\hat{p}_i^k\right)^{1-\sigma}\right]^{1/(1-\sigma)}, \tag{A21}$$

$$X_j^k \hat{X}_j^k = P_j^k C_j^k \hat{P}_j^k \hat{C}_j^k + \mathbf{1}_{k \in \mathcal{K}^c} \left(P_j^k x_j^k \hat{P}_j^k \hat{x}_j^k\right), \tag{A22}$$

$$\hat{X}_{ij}^k = \left(\hat{p}_i^k / \hat{P}_j^k\right)^{1-\sigma} \hat{X}_j^k, \tag{A23}$$

$$p_i^k Q_i^k \hat{p}_i^k \hat{Q}_i^k = \sum_{j \in \mathcal{I}} X_{ij}^k \hat{X}_{ij}^k, \tag{A24}$$

while the model under the integrated world markets assumption includes the following:

$$\hat{P}_i^k = \hat{p}_i^k, \tag{A25}$$

$$\sum_{i \in \mathcal{I}} p_i^k Q_i^k \hat{Q}_i^k = \sum_{i \in \mathcal{I}} \left[p_i^k C_i^k \hat{C}_i^k + \mathbf{1}_{k \in \mathcal{K}^c} \left(p_i^k x_i^k \hat{x}_i^k\right)\right] \text{ for all } k \in \mathcal{K}^a, \tag{A26}$$

$$\hat{Q}_i^g = \hat{x}_i^g. \tag{A27}$$

In the previous equations, with the exceptions of the behavioral parameters and the initial values of r_i^k and π_i^{fk}, all the parameters are directly observable from the data. Gouel and Laborde (2021, Section 2.3) show that equation (27) can define a contraction mapping in r_i^k. So, given the observation of total land rents R_i^k and potential yields A_i^{fk}, it is possible to recover the r_i^k, from which the π_i^{fk} can be calculated using equation (23).

B.2 Calibration of the land productivity shifter

Calibration of the land productivity shifter, A_i^{fk}, was inspired from Sotelo (2020). The GAEZ project provides information on potential not realized yields. Potential yields are yields for a field and a crop if the field were planted only with this crop and for a specific level of inputs. Following Sotelo (2020), I assume that in each country there are prices $\{p_i^{k,G}, r_i^{k,G}\}$ which rationalize the assumptions about input levels used to construct the GAEZ potential yields. It follows that there is a link between GAEZ potential yields denoted $y_i^{fk,G}$ and my model yields

$$y_i^{fk,G} = A_i^{fk} \left(\frac{r_i^{k,G}}{p_i^{k,G}}\right)^{\eta}. \tag{A28}$$

So, A_i^{fk} is the GAEZ potential yields apart from a country-crop productivity shifter $(r_i^{k,G}/p_i^{k,G})^{\eta}$. An interesting property of this model (see Gouel and Laborde, 2021, Appendix B) is that its counterfactual results are insensitive to a country-crop productivity shifter. The only information that is important for calibration and counterfactual simulations is the between-field heterogeneity for a given country-crop. This means that for simplicity, we can take $A_i^{fk} = y_i^{fk,G}$.

This approach presents one limitation in the context of climate change. I need to assume that the same set of prices that rationalizes the assumptions about input levels used for current climate conditions is used also to construct the GAEZ potential yields under climate change conditions. This would seem to be consistent with the GAEZ definition of high level inputs as yields under "optimum applications of nutrients and chemical pest, disease and weed control" (IIASA/FAO, 2021) but I cannot completely exclude the fact that some farm-level adaptations related to inputs might be embedded in the potential yields under climate change.

C Supplementary figures and tables

Table A1: Mapping between aggregate regions, countries in the model, and countries in GTAP database version 9.2

Aggregate region	Model country	Country in GTAP database
Asia	Bangladesh	Bangladesh
	China (including Hong Kong)	China; Hong Kong
	India	India
	Indonesia	Indonesia
	Japan	Japan
	Korea, South	Korea
	Malaysia	Malaysia
	Pakistan	Pakistan
	Philippines	Philippines
	Sri Lanka	Sri Lanka
	Thailand	Thailand
	Viet Nam	Viet Nam
	Rest of Asia	Mongolia; Taiwan; Rest of East Asia; Brunei Darussalam; Cambodia; Lao People's Democratic Republic; Singapore; Rest of Southeast Asia; Nepal; Rest of South Asia
Commonwealth of Independent States	Kazakhstan	Kazakhstan
	Russia	Russian Federation
	Ukraine	Ukraine
	Rest of Commonwealth of Independent States	Belarus; Rest of Eastern Europe; Kyrgyzstan; Tajikistan; Rest of Former Soviet Union; Armenia; Azerbaijan
Europe	France	France
	Germany	Germany
	Greece	Greece
	Italy	Italy
	Netherlands	Netherlands
	Poland	Poland
	Romania	Romania
	Spain	Spain
	United Kingdom	United Kingdom
	Rest of Europe	Austria; Belgium; Cyprus; Czech Republic; Denmark; Estonia; Finland; Hungary; Ireland; Latvia; Lithuania; Luxembourg; Malta; Portugal; Slovakia; Slovenia; Sweden; Switzerland; Norway; Rest of EFTA; Albania; Bulgaria; Croatia; Rest of Europe
Latin America	Argentina	Argentina
	Brazil	Brazil
	Colombia	Colombia
	Mexico	Mexico
	Peru	Peru
	Caribbean	Dominican Republic; Jamaica; Puerto Rico; Trinidad and Tobago; Caribbean
	Central America	Costa Rica; Guatemala; Honduras; Nicaragua; Panama; El Salvador; Rest of Central America
	Rest of South America	Bolivia; Chile; Ecuador; Paraguay; Uruguay; Venezuela; Rest of South America
Middle East and North Africa	Egypt	Egypt
	Iran	Iran Islamic Republic of
	Morocco	Morocco
	Turkey	Turkey
	Rest of Middle East and North Africa	Georgia; Bahrain; Israel; Jordan; Kuwait; Oman; Qatar; Saudi Arabia; United Arab Emirates; Rest of Western Asia; Tunisia; Rest of North Africa
Northern America	Canada	Canada; Rest of North America
	United States	United States of America
Oceania	Australia	Australia
	Rest of Oceania	New Zealand; Rest of Oceania
Sub-Saharan Africa	Ethiopia	Ethiopia
	Kenya	Kenya
	Nigeria	Nigeria
	Senegal	Senegal
	South Africa	South Africa
	Rest of Sub-Saharan Africa	Benin; Burkina Faso; Cameroon; Cote d'Ivoire; Ghana; Guinea; Togo; Rest of Western Africa; Central Africa; South Central Africa; Madagascar; Malawi; Mauritius; Mozambique; Rwanda; Tanzania; Uganda; Zambia; Zimbabwe; Rest of Eastern Africa; Botswana; Namibia; Rest of South African Customs Union; Rest of the World

Table A2: Product mapping between the model, GAEZ, and FAOSTAT

Model crop	GAEZ crop	FAOSTAT item
Banana	Banana	Bananas; Plantains and others
Barley	Barley	Barley
Beans	Beans	Beans, dry
Buckwheat	Buckwheat	Buckwheat
Cabbage	Cabbage	Cabbages
Carrot	Carrot	Carrot
Citrus fruits	Citrus fruits	Oranges; Tangerines, mandarins, clementines, satsumas; Lemons and limes; Grapefruit (inc. pomelos); Fruit, citrus nes
Cocoa	Cocoa	Cocoa beans
Coconut	Coconut	Coconuts
Coffee	Coffee	Coffee green
Cotton	Cotton	Seed cotton
Flax	Flax	Linseed; Flax fibre and tow
Grass	Grass	
Groundnut	Groundnut	Groundnuts, with shell
Maize	Maize	Maize; Maize, green
Millet	Pearl millet; Foxtail millet	Millet
Oat	Oats	Oats
Oil palm	Oilpalm	Palm kernels; Oil, palm
Olive	Olive	Olives
Onion	Onion	Onions, dry
Other pulses	Chickpea; Cowpea; Gram; Pigeonpea	Chick-peas, dry; Cow peas, dry; Pigeon peas; Pulses nes
Peas	Peas	Peas, dry
Rapeseed	Rapeseed	Rapeseed or colza seed
Rice	Wetland rice; Dryland rice	Rice, paddy
Rye	Rye	Rye
Sorghum	Sorghum	Sorghum
Soybean	Soybeans	Soybeans
Sugar crops	Sugarcane; Sugarbeet	Sugar cane; Sugar beet
Sunflower	Sunflower	Sunflower seed
Tea	Tea	Tea
Tobacco	Tobacco	Tobacco, unmanufactured
Tomato	Tomato	Tomatoes, fresh
Tropical roots and tubers	Sweet potatoes; Cassava; Yam and cocoyam	Sweet potatoes; Cassava; Yautia (Cocoyam); Taro (Cocoyam); Yams; Roots and tubers, nes
Wheat	Wheat	Wheat
White potato	White potatoes	Potatoes

Table A3: Welfare results using Costinot et al. (2016) parameters ($\epsilon = 1, \kappa = \varsigma = 2.82, \sigma = 5.4, \eta = 0, \theta = 1.239$)

Country[a]	Net ag. trade as % of ag. prod. (1)	Land rents as % of GDP (2)	$\delta_j - 1$ (%) (3)	$\delta_j^* - 1$ (%) (4)	Welfare change (% of GDP): Production fn. (5)	Welfare change (% of GDP): Supply-side (6)	Welfare change (% of GDP): Exact (7)	$\text{Bias}_j / \Delta W_j$ (%) (8)
Argentina	60.64	1.24	16.17	19.23	0.20	0.24	0.06	−314.39
Australia	34.77	0.28	−47.33	−44.65	−0.13	−0.13	−0.07	−91.98
Bangladesh	−31.37	3.17	−30.03	−28.33	−0.95	−0.90	−2.55	64.67
Brazil	38.01	0.67	−26.04	−23.25	−0.17	−0.15	−0.01	−2305.57
Canada	25.36	0.16	17.99	50.65	0.03	0.08	−0.04	285.50
China (including Hong Kong)	−4.92	1.95	21.49	48.78	0.42	0.95	0.39	−143.75
Colombia	4.46	1.24	−35.00	−29.85	−0.43	−0.37	−0.46	19.96
Egypt	−67.51	0.31	−79.96	−53.68	−0.25	−0.17	−0.88	80.97
Ethiopia	0.70	4.80	45.78	65.48	2.20	3.14	−0.54	679.05
France	17.59	0.19	−5.38	−4.06	−0.01	−0.01	−0.01	15.60
Germany	−7.36	0.16	10.43	11.34	0.02	0.02	−0.02	214.32
Greece	−9.58	0.81	0.83	7.18	0.01	0.06	−0.09	161.79
India	4.81	4.72	−18.01	−14.48	−0.85	−0.68	−1.37	50.05
Indonesia	−7.78	4.94	−22.91	−20.39	−1.13	−1.01	−1.67	39.57
Iran	−15.04	0.42	70.90	122.20	0.30	0.51	0.11	−378.27
Italy	−23.46	0.22	−3.45	7.66	−0.01	0.02	−0.05	131.79
Japan	−31.64	0.18	38.17	59.25	0.07	0.11	0.04	−149.77
Kazakhstan	−1.14	0.61	32.69	64.88	0.20	0.40	0.02	−1900.95
Kenya	4.85	1.29	1.55	13.63	0.02	0.18	−0.53	132.92
Korea, South	−49.81	0.52	53.80	56.48	0.28	0.29	0.17	−68.25
Malaysia	−30.05	2.72	−5.67	−5.40	−0.15	−0.15	−0.48	69.06
Mexico	−18.08	0.46	−15.68	−7.88	−0.07	−0.04	−0.05	26.04
Morocco	−26.88	0.82	−87.95	−87.03	−0.72	−0.71	−2.43	70.84
Netherlands	−16.22	0.12	20.32	21.18	0.02	0.02	−0.09	126.31
Nigeria	−9.83	1.38	−27.29	−24.64	−0.38	−0.34	−1.52	77.63
Pakistan	1.86	3.07	−24.41	−19.52	−0.75	−0.60	−1.07	44.14
Peru	−5.98	1.39	90.79	213.56	1.26	2.97	0.78	−281.95
Philippines	−0.77	3.20	−16.29	−15.02	−0.52	−0.48	−0.51	6.46
Poland	2.30	0.84	−2.70	61.83	−0.02	0.52	−0.06	964.89
Romania	−2.06	1.82	−18.14	−17.75	−0.33	−0.32	−0.38	13.92
Russia	−8.84	0.54	0.51	7.00	0.00	0.04	−0.02	272.47
Senegal	−45.00	1.23	−66.55	−63.50	−0.82	−0.78	−2.91	73.14
South Africa	1.42	0.21	−11.42	−4.91	−0.02	−0.01	−0.04	74.37
Spain	1.73	0.20	−33.59	−25.40	−0.07	−0.05	−0.04	−17.78
Sri Lanka	−38.03	1.94	−30.25	−28.27	−0.59	−0.55	−1.22	55.22
Thailand	20.42	2.52	−44.61	−42.30	−1.12	−1.07	−1.14	6.45
Turkey	−7.16	0.48	36.48	52.84	0.17	0.25	0.02	−1176.23
Ukraine	30.74	1.82	−21.77	−21.34	−0.40	−0.39	−0.13	−195.21
United Kingdom	−38.08	0.14	31.56	34.20	0.05	0.05	0.00	−4002.02
United States	15.37	0.26	−5.52	5.93	−0.01	0.02	−0.02	173.94
Viet Nam	−1.80	6.56	−19.49	−16.73	−1.28	−1.10	−1.22	9.66
Asia	−5.92	1.82	−0.01	13.96	−0.00	0.25	−0.11	330.20
CIS[b]	−1.49	0.77	6.66	29.79	0.05	0.23	−0.01	1970.36
Europe	−5.18	0.25	−0.88	11.38	−0.00	0.03	−0.03	191.40
Latin America	23.68	0.81	−16.01	−6.14	−0.13	−0.05	−0.07	28.53
Middle East and North Africa	−39.36	0.29	10.80	30.35	0.03	0.09	−0.18	147.09
Northern America	16.58	0.25	−4.00	8.82	−0.01	0.02	−0.02	195.20
Oceania	37.33	0.35	−31.42	−25.01	−0.11	−0.09	−0.06	−54.17
Sub-Saharan Africa	−3.06	1.39	−23.72	−18.62	−0.33	−0.26	−1.15	77.65
World	0	0.78	−2.50	10.90	−0.02	0.08	−0.09	198.63

Notes: Columns 3 and 4 represent the aggregate change in crop production using land rents as weight and assuming, respectively, no adaptation and adaptation through acreage changes at constant prices. Columns 5 and 6 can be obtained by multiplying column 2 by, respectively, columns 3 and 4.
[a] Only countries represented individually in the model are presented here. [b] Commonwealth of Independent States.

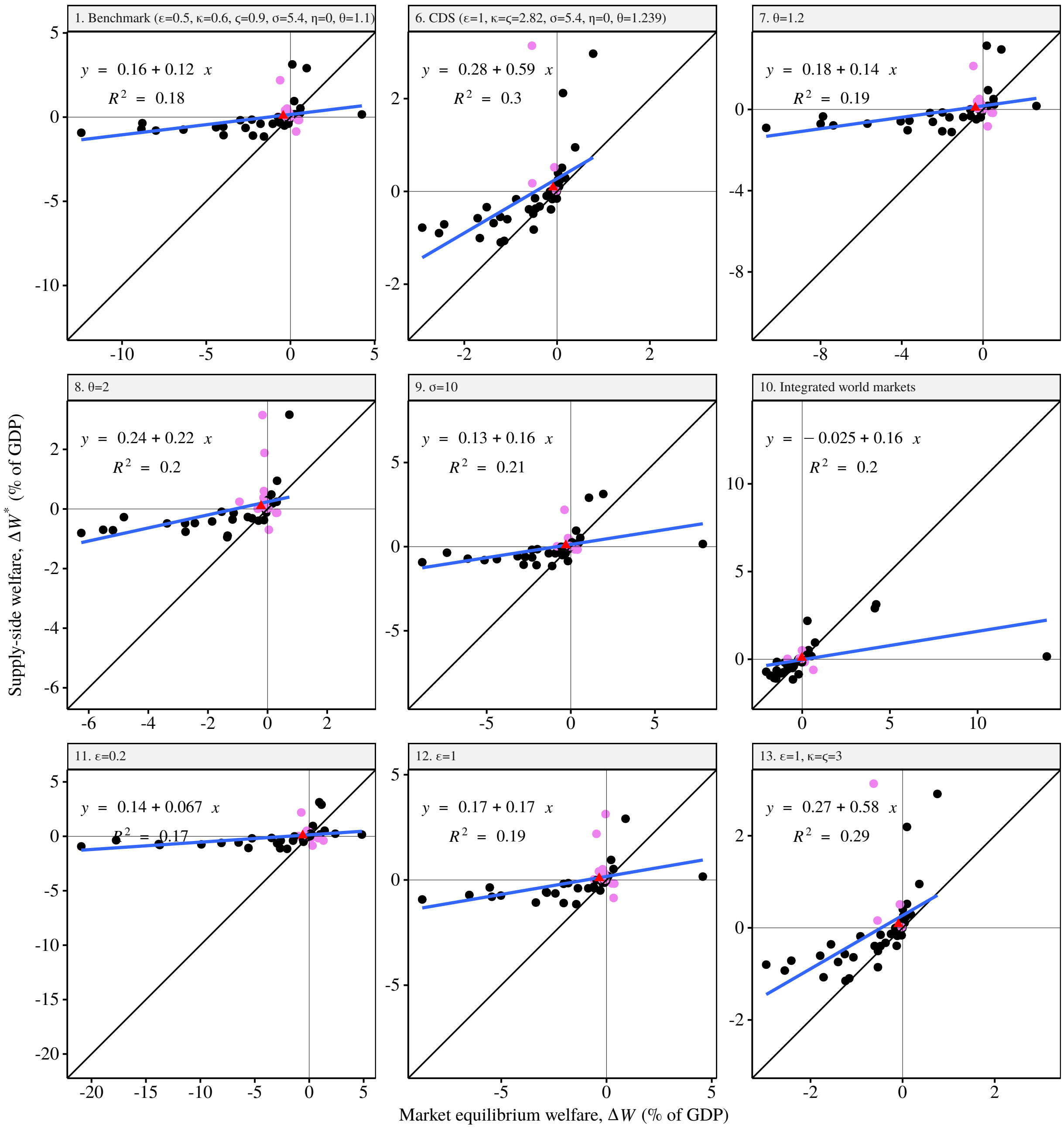


Figure A1: Additional results on the role of model assumptions in the bias of the supply-side approach. Notes: pink points indicate countries whose welfare measures have opposite signs, the red triangles are world welfare, and the blue lines are the regression lines displayed also as equations in the top-left part of each panel. With the exception of panels 1 and 6, panel titles correspond to the assumptions and parameters that have changed, with the remaining assumptions and parameters as in the benchmark situation. In panel 6, CDS stands for Costinot et al. (2016).

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