Supplementary Appendix to
Measuring Climate Change Impacts on Agriculture:
An Equilibrium Perspective on Supply-Side Approaches*

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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,

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$A^{k\prime}$ 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 $i, j \in \mathcal{I}$, $k \in \mathcal{K}$:

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

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

$$\hat{x}_j^k = \left(\hat{P}_j^k/\hat{P}_j^{\text{feed}}\right)^{-\varsigma}\hat{Q}_j^{1} \text{ for all } k\in\mathcal{K}^c, \tag{A17}$$

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

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

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

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 Sensitivity analysis

This sensitivity analysis addresses three potential concerns related to the paper’s 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.

C.1 Model calibration

C.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.

Table A1 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. 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 paper's conclusions.

C.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, 2023). Table A2 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 A2). 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.

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 A2 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 A2 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.

C.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. 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.

Table A1: Welfare results using Costinot et al. (2016) parameters ($\epsilon = 1, \kappa = \varsigma = 2.82, \sigma = 5.4, \eta = 0, \theta = 1.239$)

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

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.

The role of the demand elasticity for the food bundle is analyzed in panels 11 to 13. Given that the supply-side

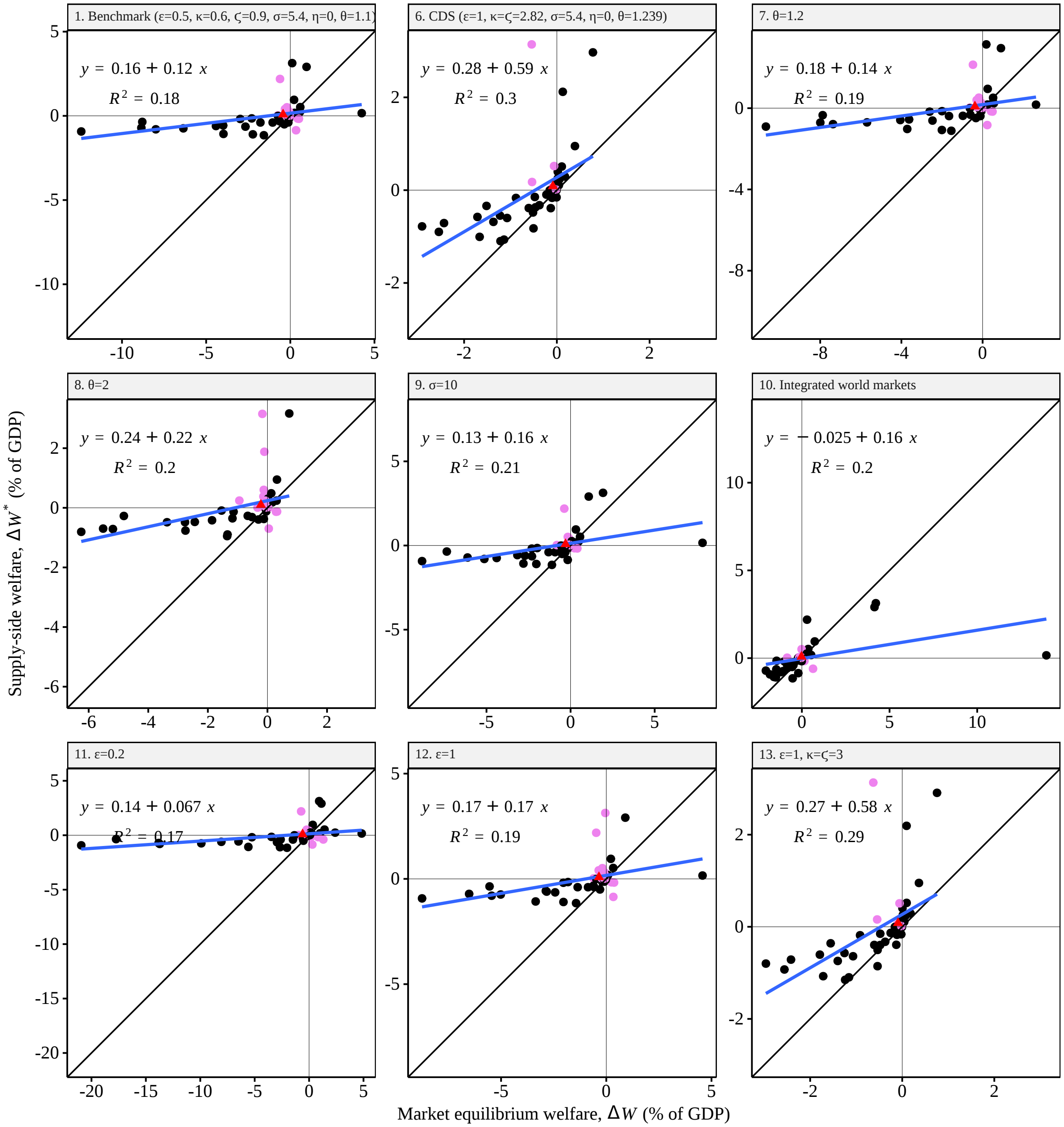

Figure A1: Additional results on the role of model assumptions in the bias of the supply-side approach. Notes: pink points indicate countries whose welfare measures have opposite signs, the red triangles are world welfare, and the blue lines are the regression lines displayed also as equations in the 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).

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

Table A2: 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

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.

C.2 Climate scenario

In the paper, 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 A3 analyzes all these possible combinations.[1] 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 a non-negligible supply-side approach bias. The low R^2 from regressing supply-side welfare on market equilibrium welfare confirms that the bias matters also 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.

C.3 A marginal climate change shock

Econometric 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 A4 reports the results under the two trade assumptions, Armington and integrated world market.

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

Table A3: Results for different climate scenarios

		Without CO_2 fertilization			With CO_2 fertilization		
Climate	RCP	Global welfare ch. (% of GDP)		R^2 of	Global welfare ch. (% of GDP)		R^2 of
model	scenario	Supply-side	Exact	$\Delta W^* \sim \Delta W$	Supply-side	Exact	$\Delta W^* \sim \Delta W$
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 A4: Results for marginal shocks

Trade	Share of	Global welfare change (% of GDP)		R^2 of
assumption	yield shock (%)	Supply-side	Exact	$\Delta W^* \sim \Delta W$
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

Table A4 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 A4 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 A4 show the effects of marginal shocks under the integrated-world-market assumption: the relative price changes are more 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 $\delta_k \longrightarrow 1$).[2] However, the two-country model biases would converge to non-zero values,[3] 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.

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

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

D Supplementary figures and tables

Table A5: 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 A6: 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

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