The Impact of Global Warming on Agriculture: A Critique of the Ricardian Approach from a General Equilibrium Perspective*

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PRELIMINARY AND INCOMPLETE

Abstract

The Ricardian approach is a popular reduced-form approach for estimating climate change impacts on agriculture. This approach focuses 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 Ricardian approach as well as to calculate exact welfare changes. The model shows that both welfare measures are weakly correlated and can be of opposite signs, and that the Ricardian 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 Ricardian 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.

Keywords: adaptation, agriculture, climate change, international trade, land use, Ricardian analysis.

JEL classification: D58, F18, Q17, Q54, R14.

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1 Introduction

The Ricardian approach pioneered by Mendelsohn et al. (1994) is likely the most popular method for estimating the economic consequences of climate change on agriculture, with applications on most countries in the world with available data on farmland values (Mendelsohn and Massetti, 2017). Its appeal rests on its simplicity and transparency. It involves two steps. First, estimate the effect of climatic variables (temperature, precipitation) on net revenue or land value of farms on cross-sectional or panel data. Second, combine this estimation with projections of the climatic variables under climate change to obtain the economic effects of climate change through the changes in land value. The Ricardian approach is by essence a hedonic approach considering that market prices, in this case for land, incorporate all the information about the relevant local production conditions. Hedonic approaches are best suited for analyzing local issues where changes of the amenities are unlikely to affect market equilibrium with feedback effects on the estimated values of these amenities. The amenities under consideration in the Ricardian approach are the effects of climate on crop growing conditions as materialized in land rents. The problem with this approach is that climate change is not a local issue; it has global effects. If the global impact of climate change is heterogeneous enough between crops, it may lead to large changes in relative crop prices with subsequent effects on the valuation of the climate impact, invalidating the hedonic foundations of the Ricardian approach.

The objective of this paper is to analyze the potential bias of using the Ricardian approach instead of a quantitative general equilibrium model accounting for all price changes in agriculture. It focuses on two sources of bias of the Ricardian approach. First, the neglect of relative price changes between crops caused by the fact that the climate change shock has heterogeneous effects on crops and crops are imperfect substitutes. Second, the neglect of 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 very close to Gouel and Laborde (2018), which presents all the required elements. The theoretical structure of the equilibrium model is used to mimic a Ricardian approach by calculating the changes in land rents caused by climate change accounting for farmers' adaptation (i.e., switching crops) at constant prices. This approach allows the welfare under the Ricardian approach and the welfare accounting for price adjustments to be comparable and to study the conditions of validity of the Ricardian approach.

This paper makes two main contributions. First, it shows that, in the general setting of a multi-crop open-economy model, the Ricardian approach is likely to provide biased estimates of the welfare effects of climate change. The welfare changes obtained from the Ricardian approach are weakly correlated with the exact welfare changes calculated as equivalent variations. This is explained by the fact that climate change has heterogeneous impacts on crop yield. The yield of some crops increases in average while it decreases for others; thus, their relative prices change if crops are imperfect substitutes. These relative price changes also create terms-of-trade changes depending on the countries trade situation. These effects can be switched off by assuming crops to be perfect substitutes and trade to be costless, conditions under which the Ricardian approach is valid.

Second, this paper provides an analytical framework that allows comparing consistently the three existing approaches used in economic analysis of the impacts of global warming on agriculture: the production function, the supply-side, and the market equilibrium approaches. The production function approach analyses the effect of climate change by estimating how much crop yields would change under the new climate accounting for some farm-level adaptations such 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 values of production or the land rents to convert them into an economic measure of the impact. The supply-side approach, in which the Ricardian approach is the most popular, assesses the welfare effect of climate change by accounting, in addition to the technological adaptions considered in the production function approach, for other adaptations operating through the land market, such as switching to more profitable crops, but neglecting the adaptations related to the changes in crop prices, those being assumed constant (Mendelsohn et al., 1994; Fisher et al., 2012; Deschênes and Greenstone, 2007). Lastly, the market equilibrium approach accounts in addition for the adaptation mediated by changes in market prices, both within- and between-countries.

For a long time, the supply-side and the market equilibrium approaches had very different spatial focuses; thus, they were not comparable. The supply-side approach is mostly applied at the country level and works in this tradition account with details for within-country heterogeneity. On the other hand, works based on market equilibrium models often 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). Therefore, supply-side works took into account adaptation through within-country reallocations, while equilibrium models focused more on the adaption through between-country reallocations. Thanks to the availability of detailed spatial data at the world level (e.g., IIASA/FAO, 2012) and increased computational power, it has recently become possible to account in the same equilibrium model for within- and between-country reallocations as demonstrated by Costinot et al. (2016). In this paper, I build on the recent work of Costinot et al. (2016), extended in Gouel and Laborde (2018), and incorporate in the same model the three approaches that have been used to estimate the economic effect of climate change.[1]

This work is related to other works emphasizing the potential bias of reduced-form estimations when they neglect some key market reactions. For example, Bergquist et al. (2019) on agricultural policy interventions or Heckman et al. (1998) on tuition policy. Both papers show that, when policies are scaled from local interventions to national ones, general equilibrium effects can lead to very different welfare effects than the econometric results would have predicted. Both papers could point toward the complementarity between the econometric estimation of treatment effects that allows for clean identification of local effects and general equilibrium models to assess how policies would scale. In the present case, there is no such complementarity as it is unclear how Ricardian estimates could be used in a general equilibrium model.

This critic of the Ricardian approach is not a new one. It has been clear at least since Cline's (1996) comment that the Ricardian approach is a supply-side analysis where agricultural prices are assumed to remain constant. In addition, several articles using trade models have shown that climate change could generate large terms-of-trade effects that would be crucial in welfare assessment (e.g., Darwin et al., 1995; Gouel and Laborde, 2018; Baldos et al., 2019) and that cannot be accounted for with a supply-side analysis. However, Cline's concern that assuming constant prices could strongly bias the welfare assessment was dismissed by Mendelsohn and Nordhaus (1996) based on a simple Marshallian analysis showing that the bias is likely to be small. In section 2, I reproduce Mendelsohn and Nordhaus's example and confirm the authors' results of a bias small enough to be neglected; but this example is too restrictive. I extend it to an open-economy setting with which I show that the bias at the country level of the Ricardian approach can become arbitrarily large in open economy. The same is also shown with a two-crop closed-economy general equilibrium model, where the neglect by the Ricardian approach of the limited substitutability between crops on the demand side can lead to severe biases.

Then, to go 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 (2018) model and includes features allowing it to mimic a Ricardian analysis done on every country in the world, but the model can also be used to calculate the welfare effects of climate change accounting for price changes. These two measures of welfare will allow us to assess the bias of the Ricardian approach, the model accounting for all the potential sources of bias identified in section 2. For the model to be able to mimic a Ricardian analysis, it requires two features that are not common in trade models applied to the agricultural sector. First, it requires a rich within-country spatial heterogeneity as in Costinot et al. (2016), but contrary to most GTAP-based applications where land is represented with one field per country (Baldos et al., 2019) or a few fields defined by land classes (Darwin et al., 1995). Within-country spatial heterogeneity allows accounting for the within-country reallocations that are at the heart of the Ricardian approach. Here, land is represented by a collection of fields defined as pixels on a 1-degree grid, so the model includes 12,000 fields each with their potential productivity of land. Second, it requires several crops with heterogeneous exposition to climate change. One of the key insights of Mendelsohn et al. (1994) was that climate change is likely to have very different impacts depending on the crops and

[1]The objective of Darwin (1999) was similar to this paper's objective: 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, it could not capture the rich within-country adjustments that should be captured by the Ricardian approach. In addition, Darwin (1999) does not address the key question of the conditions of validity of the Ricardian approach.

their locations. Focusing only on the major grains as is common in the literature given their importance for food security (e.g., Baldos et al., 2019) overlooks the fact that under climate change they could be replaced by crops generating much higher value per hectare. To account for possibilities of rich substitution between crops, the model covers 35 crops including grass for representing pastures, so it represents most agricultural land uses.

This model is then calibrated in section 4. The calibration is based, for both the initial equilibrium and the elasticities, on Gouel and Laborde (2018). For the initial equilibrium, a key data source is the GAEZ project (IIASA/FAO, 2012), which provides information about crop potential yields under current climate and which is used also for the information about the potential yields under climate change. The behavioral parameters are based on a literature review done in Gouel and Laborde (2018), which shows that most of the literature points to small elasticities for food products on the demand and the supply side (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 in calculating welfare *per se* but in analyzing under which conditions the welfare change obtained by the Ricardian approach is a good approximation of the exact welfare change. So, the chosen calibration serves only as a central case to discuss in details the differences between the Ricardian and the exact welfare changes. To mitigate concerns about the role of this central calibration, the main results obtained using Costinot et al. (2016) behavioral parameters, representative of a situation where demand and supply are more elastic, are presented in Appendix C and confirm the results of the central calibration.

Section 5 presents the results obtained from the quantitative trade model. I consider two types of results. The first result is a comparison of the three welfare measures (production function, Ricardian, and exact) under the central calibration. It shows that the production function and Ricardian approaches have similar order of magnitudes, because both measures are by construction proportional to initial land rents. The production function welfare change is inferior to the Ricardian welfare since it neglects adaptation through the land markets. The exact welfare change does not necessarily have the same order of magnitude as the other two measures. Its magnitude depends on the local food scarcity caused by climate change. In addition, once market-mediated adaptations are accounted for, welfare changes can be below or above Ricardian welfare changes with possibly different signs. The second result is an exploration of the conditions under which the Ricardian approach provides a good approximation of the exact welfare changes. This is done by changing the model's assumptions and behavioral parameters and analyzing how they affects the correlation between Ricardian and exact welfare. The Ricardian approach provides an almost perfect approximation of the exact welfare change only if agricultural products are perfect substitutes and trade costs are neglected.

2 Simple examples

This section presents simple textbook examples to illustrate the size of the bias of the Ricardian approach in various settings. These examples will inform the discussion of the respective role of the various mechanisms in the subsequent sections. In the examples below, welfare changes from climate change, ΔW, are decomposed into the welfare changes as captured by the Ricardian approach, ΔW^*, and a bias:

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

The counterfactual value after climate change of a variable v is denoted as v' and the counterfactual value under the Ricardian approach is denoted v^*.

2.1 Single country model

To begin, consider an example discussed in Mendelsohn and Nordhaus (1996) in a reply to Cline's (1996) comment that the Ricardian approach was biased because of the neglect of price changes. Mendelsohn and Nordhaus (1996) propose to analyze the bias related to neglecting price changes using a simple Marshallian approach in a closed economy. Representing the agricultural sector by linear demand and supply curves as in figure 1, they explain that climate change can be represented by a translation to the left of the supply curve and the Ricardian approach would be equivalent as assessing its effect as the reduction in producer surplus at constant prices. This assessment neglects the price increase, which leads to a reduction in demand and an increase in supply lower than the initial shock, and a bias corresponding to the two purple triangles in the figure. So, the Ricardian approach underestimates the welfare loss from a negative climate change shock.

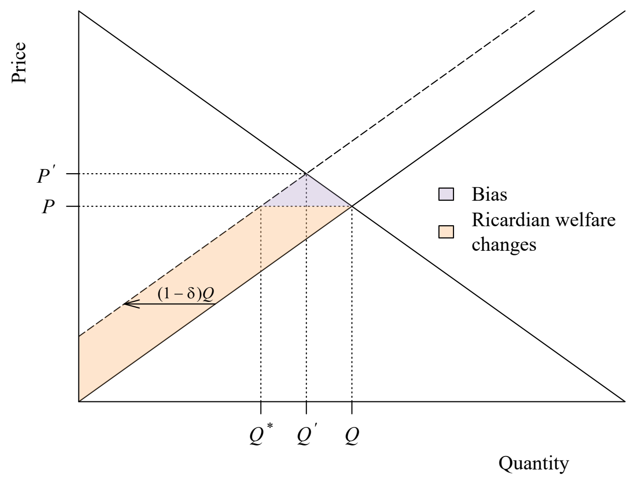


Figure 1: Bias of the Ricardian approach in a closed-economy. Initial equilibrium (Q, P) and equilibrium after climate change (Q', P'). Climate change is represented as a reduction of the intercept of the supply curve by $(1 - \delta)Q$.

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

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

where $\eta, \epsilon > 0$ are supply and opposite of demand elasticities at the 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 shock and $\delta < 1$ a negative supply shock. The bias is positive for negative supply shocks and negative for positive supply shocks. So, the Ricardian underestimates the welfare cost of a negative climate change shock. The bias increases in absolute values with the values of the demand and supply elasticities and its limit if $\epsilon \to 0$ or $\eta \to +\infty$ is $(1 - \delta)/2$. So, for a 10% supply reduction the bias does not exceed 5% of the total losses, and 12.5% for a 25% supply reduction. These results confirm the intuition from figure 1 that in closed economy the bias is small compared to total losses.

Note, though, that by construction the Ricardian approach focuses on assessing the 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, equal to $(P' - P)Q'$. These transfers can be large and even equal to the total welfare changes in the limit case of $\epsilon \to 0$. The neglect of transfers, which is inconsequential in closed economy, is what explains that the bias can become much larger in open economy.

2.2 Two-country model

Consider now 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 the equilibrium under current climate, demand and supply elasticities are the same in both countries. Climate change is represented by a shift in the intercepts of the supply curves, respectively, by $(1 - \delta_h)Q_h$ and $(1 - \delta_f)Q_f$. Figure 2 represents a situation with a climate change shock of the same relative intensity in each country ($\delta = \delta_h = \delta_f$).

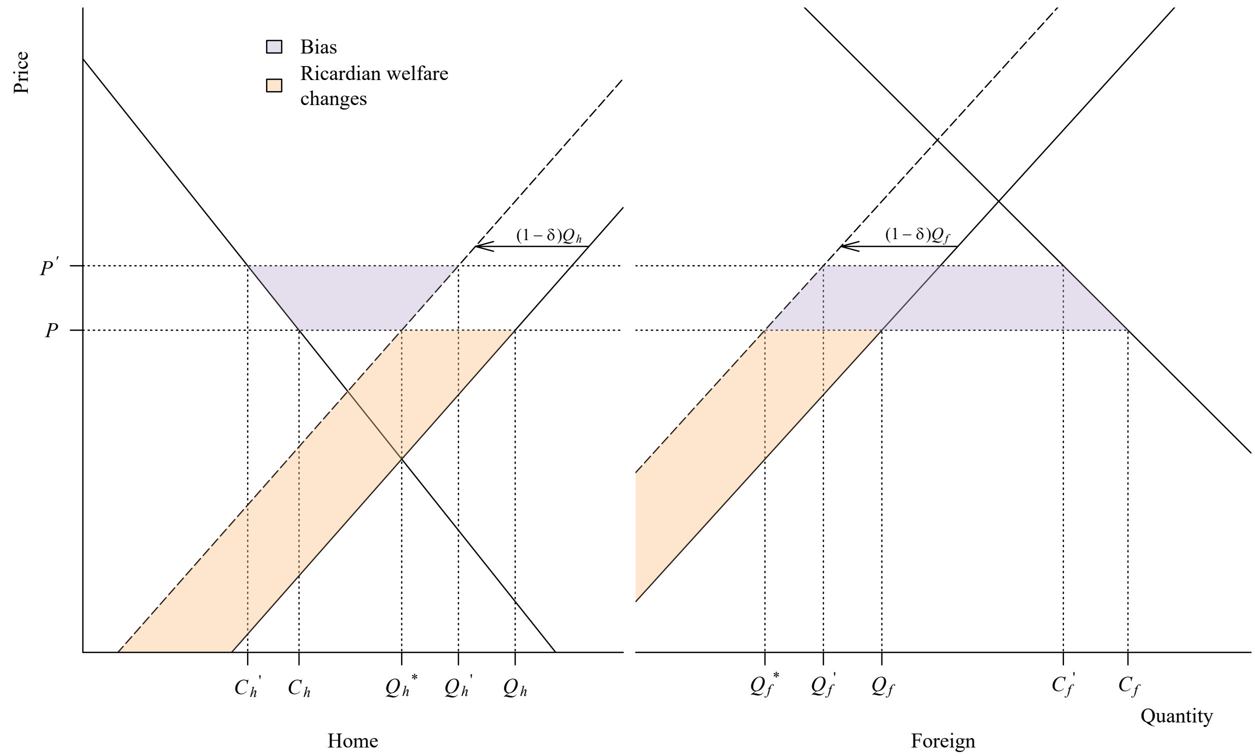


Figure 2: Bias of the Ricardian approach in a two-country model. Initial equilibrium (C_h, C_f, Q_h, Q_f, P) and equilibrium after climate change $(C'_h, C'_f, Q'_h, Q'_f, P')$. Climate change is represented as a reduction of the intercept of the supply curves by, respectively, $(1-\delta)Q_h$ and $(1-\delta)Q_f$.

The bias of the Ricardian approach increases in size from a triangle in closed economy to trapezoids in open economy with one base related to the size of trade under climate change. In Home, the exporting country, the bias is negative. The Ricardian 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. The Ricardian 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 higher for the importer than for the exporter, in absolute value. Since, the biases have opposite signs, they partially cancel when summed, and the aggregate bias is the same as the one obtained in the one-country model before.

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

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

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

where $x_h = (Q_h - C_h)/Q_h$ and $m_f = (C_f - Q_f)/Q_f$ are the ratios to domestic production of Home export and Foreign import. 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 share of exports in production. For an export share lower than $(\eta+\epsilon)(1-\delta)/[2\eta+(1+\delta)\epsilon]$, the bias is positive. It turns negative for higher export shares.

While it is also possible to characterize analytically the biases when shocks are different between countries, the expression of the biases are too cumbersome to be of use. Instead, I provide a numerical illustration of the size of the biases under various situations of symmetric and asymmetric shocks in table 1. For this, 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 (case 1 in table 1) is a situation of symmetric shocks with $\delta = 0.9$, $\epsilon = 0.5$, $\eta = 0.5$, and $x_h = m_f = 0.25$. The bias will always be negative here for Home, given that the export share threshold under which the bias is negative is equal to 5.1%.

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. $(0.90, 0.5, 0.5, 0.25)$	−11.4	13.4	2.6
2. $(0.90, 1.0, 0.5, 0.25)$	−7.2	9.3	1.7
3. $(0.90, 0.2, 0.5, 0.25)$	−17.3	18.2	3.6
4. $(0.90, 0.5, 1.0, 0.25)$	−15.9	17.2	3.4
5. $(0.90, 0.5, 0.2, 0.25)$	−6.1	8.0	1.5
6. $(0.90, 0.5, 0.5, 0.25, \delta_h = 0.95)$	−33.3	11.0	2.6
7. $(0.90, 0.2, 0.5, 0.25, \delta_h = 0.95)$	−56.5	15.1	3.6
8. $(0.90, 0.5, 1.0, 0.25, \delta_h = 0.95)$	−50.1	14.2	3.4
9. $(0.90, 0.5, 0.5, 0.25, \delta_h = 0.85)$	−5.5	20.0	2.6
10. $(0.90, 0.5, 0.5, 0.50)$	−29.9	22.1	2.6
11. $(0.75, 0.5, 0.5, 0.25)$	−6.7	17.0	6.7
12. $(0.75, 0.5, 0.5, 0.50)$	−24.4	25.3	6.7
13. $(0.75, 0.5, 0.5, 0.25, \delta_h = 0.90)$	−51.8	16.6	7.0
14. $(0.75, 0.5, 0.5, 0.50, \delta_h = 0.90)$	−185.4	22.5	7.0

Notes: Home and Foreign are assumed to have the same production level under current climate, so $x_h = m_f$. [a] The symbols $(\delta, \epsilon, \eta, x_h)$ 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, respectively.

Table 1 presents the bias for each country and for both together. Confirming Mendelsohn and Nordhaus's (1996) results exposed in the previous section, the global bias is always small and positive. It is not affected by the exported share or by the shock allocation between countries, just by the global shock and the elasticities. Country-level biases, however, are an order of magnitude higher, but since they are of opposite sign, they tend to compensate one another at the global level. Comparing cases 1–8, the size of the bias increases at the country and at the global level with a more inelastic demand or a more elastic supply. The influence of the elasticities on the country-level biases depends on the asymmetry of the shocks. For symmetric shocks (cases 1–5), the elasticities have symmetric effect on the bias. For asymmetric shocks (cases 6–8), the bias in the country with the largest bias in the symmetric case tends to increase much more with a change in one of the elasticities.

Asymmetric shocks leave the global bias unaffected but increase the bias in one country while reducing it in another. For example, when the shock is smaller in the exporting country than at the global level (cases 6–8 and 13–14), the bias becomes much more important in the exporting country, with the Ricardian welfare reaching almost 3 times the true welfare change in case 14. In this situation, the Ricardian welfare change becomes smaller, while the terms-of-trade change that is the big part of the bias becomes larger (same counterfactual price but larger exports).

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 comes from the fact that the bias is the sum of two terms, one common to both countries with a positive sign, corresponding to the global bias, and one specific to the trade situation with opposite signs, corresponding to the terms of trade. With a larger shock, the first term increases more than the second and the bias decreases for the exporting country.

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

This toy model makes clear some of the key parameters that are susceptible to drive a large bias of the Ricardian approach in open economy: 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 at the world level, a Ricardian approach applied at the world level would have the small bias identified in the single-country example. In practice, given its heavy data requirement, this method is applied at the country level, with very few exceptions at the continental level (Kurukulasuriya et al., 2006, apply it to 11 African countries, and Passel et al., 2017, at the European level), so the bias created by terms of trade cannot be eliminated. In addition, the next example shows that even in 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 land with endowment L.[2] 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 by 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 $A^{k\prime} = \delta^k A^k$.

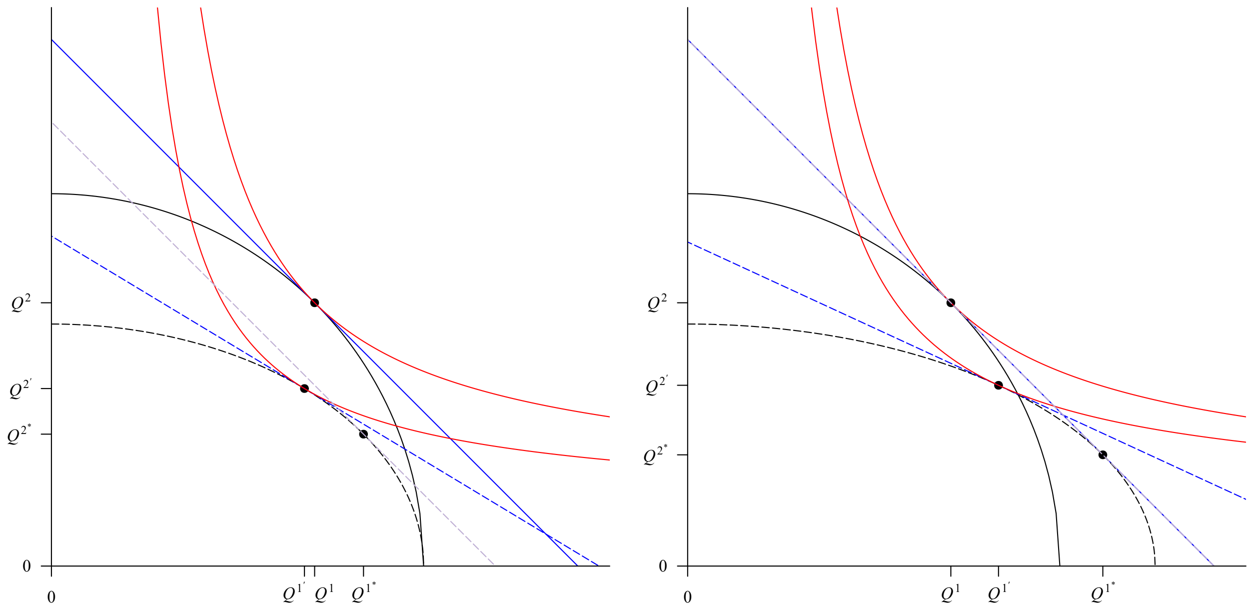
Figure 3 represents the behavior of this model under two different climate change shocks. Climate change leads to changes in the production possibility frontier (PPF). Under the assumption of constant prices, the production under the Ricardian approach, (Q^{1^*}, Q^{2^*}), is located at the tangent of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

Under this setting, and denoting by α^k the budget share of crop k under current climate, Appendix A proves that the ratio of the bias to total welfare changes is given by

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

This expression of the bias brings the following remarks. (i) The Ricardian (numerator) and true welfare changes (denominator) have similar expressions, but the elasticity of substitution between crops appear in the true welfare change but not in Ricardian welfare change. (ii) Because $\kappa > 0$, by the generalized means inequality, the utility under the Ricardian approach is always superior or equal to the true utility under climate change, so the Ricardian 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 Ricardian approach delivers the exact welfare changes. (iv) Similarly, 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

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



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

(b) No welfare changes with the Ricardian 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 Ricardian approach with the two-crop model

shock can be summarized by an income shock evaluated on the land rents. For further intuitions on the bias, numerical illustrations are used.

Table 2 illustrates the behavior of this model in a setting where crops have initially the same budget share by varying θ, κ, and the δ^k. The table displays the aggregate first-order shock, $\delta = \sum_{k=1}^{2} \alpha_k \delta^k$, the Ricardian welfare change, the true welfare change, and the bias of the Ricardian approach. Following the theoretical predictions, the Ricardian approach always lead to an underestimation of the losses, so a positive bias. Contrary to the previous examples, the size of the bias has nothing to do with the size of the shock but is related to the heterogeneity of the shocks across crops, mediated by the elasticities of substitution and transformation. Comparing cases 1 and 4, this is even the opposite: for the same shock dispersion around the average (measured in standard deviation), the bias is smaller for a larger shock. In cases 1–3, only the dispersion of the shock is changed and the bias increases from 0% to 43.1%. In the situation of case 5, where the first-order shock is zero because the productivity increase in one crop compensates the decrease in the other, the bias exceeds 100 meaning that the Ricardian welfare change has the wrong sign. One can also note that case 2 where the Ricardian approach has no bias is also a case where the Ricardian approach has no interest because it is equivalent to a simple production function approach: $\delta - 1 = \Delta W^*/L$.

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

θ has a limited effect on true welfare changes (lower than the number of digits printed in table 2), but much more on Ricardian welfare changes, so the bias increases with θ (cases 1 and 8–10). Even though the Ricardian approach

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, so $\alpha^k = 0.5$. [a] The symbols $(\theta, \kappa, \delta^1, \delta^2)$ denote one minus the elasticity of transformation between crops, the elasticity of substitution between crops, and the size of the production shocks (no shock is $\delta^k = 1$), respectively.

accounts for reallocation between crops because of productivity changes and because of this depends on the value of θ, this does not purge the bias from the influence of θ, because the effect of relative price changes on crop reallocation is also mediated by θ.

Lastly, as expected, the bias decreases with the elasticity of substitution, κ. Here the effect is opposite to the one of θ. κ has no effect on Ricardian welfare but decreases the true welfare losses, decreasing the bias (cases 1, 6, and 7).

This two-crop model is a closed economy example, without other goods than the crops (so with an inelastic demand for the crop bundle), and without the possibility to produce more of a crop except by producing less of another (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 three biases would be compounded.

Finally, there are two things to add. First, by Jensen inequality, the Ricardian approach leads to welfare losses lower than under a production function approach represented in the table by the column $\delta - 1$. Second, true welfare can be below or above the production function approach, depending on the parameter's values. It exceeds the production function welfare if $\kappa \geq 1 + \theta/(\theta - 1)$. For κ high enough, as in case 7, true welfare converges to Ricardian welfare 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 Ricardian approach should lead to an under-evaluation of the cost of climate change, because of the neglect of imperfect substitution between crops (section 2.3) and the neglect of the overall market reaction (section 2.1). However, if terms-of-trade effects are large enough, the bias of the Ricardian approach can change sign for exporting countries, so an over-evaluation of the losses could be expected for large food exporters (section 2.2). But, since terms of trade are just transfers between countries, they won't affect the average under-evaluation at the world level.

3 Model

This section presents a model of global agricultural trade and land use that can be used to mimic the results of an ideal Ricardian approach as well as calculating theoretically exact welfare changes. The model follows that of Gouel and Laborde's (2018) model, with one difference: the accounting of substitution between land and non-land inputs in crop production. The model includes all the potential sources of bias seen previously, as well as two additional ones. It follows the notations used in the previous section, with the elasticities having the same interpretations. However, its structure is simpler that many GTAP-based CGE models used in this literature (e.g., Darwin, 1999; Baldos et al., 2019). Among the many differences, my model assumes a demand for food inelastic to income, a constant price for the non-land input in crop production, and a fixed agricultural land area. The specific roles of these assumptions will be discussed later, but they all share the fact that they limit the general equilibrium mechanisms to the agricultural sector. In developed countries, where the agricultural sector represents a small share of economic activities, such assumptions are likely innocuous. This would be less so in developing countries, but the neglect of these mechanisms is a minor issue given this paper's objective. The Ricardian approach also neglects these general equilibrium mechanisms, so these modeling choices limit the bias of the Ricardian approach to the previously identified mechanisms that are likely to be the most important ones.

3.1 Model setup

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

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

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.

Regarding the preferences over agricultural goods with different countries of origin, I consider two approaches: an Armington assumption and a homogeneous good assumption. The Armington assumption, combined with multiplicative trade costs, will lead to a standard gravity specification for trade. It also means 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 Ricardian approach related to them as analyzed in section 2.2. To be able to avoid this additional bias and to allow the model to exactly replicate the Ricardian approach, I also consider a version of the model where agricultural goods are assumed to be homogeneous products.

Under the Armington assumption, the final consumption of each agricultural good, but not the non-agricultural good, is itself a CES function of the consumption of varieties from different origins:

$$C_j^k = \left[\sum_{i\in\mathcal{I}} \left(\beta_{ij}^k\right)^{1/\sigma} \left(C_{ij}^k\right)^{(\sigma-1)/\sigma}\right]^{\sigma/(\sigma-1)} \quad \text{for all } k \in \mathcal{K}^a, \tag{10}$$

where $\sigma > 0$ and $\neq 1$ is the elasticity of substitution between varieties from different regions, C_{ij}^k is the export for final consumption from region i to region j of good k, and $\beta_{ij}^k \geq 0$ is an exogenous preference parameter.

Technology

Non-agricultural good The non-agricultural good is produced with labor only and constant return to scale with $A_i^0 > 0$ representing labor productivity.

Crops Crops are produced using land and labor, combined using a CES function with elasticity $\eta \in [0, 1)$. Instead, it could have been assumed, as Costinot et al. (2016) and Gouel and Laborde (2018) did, that land and labor are complementary and intensification could have been introduced by allowing some substitution with the outside good. However, in this model where wages and the price of the outside good are constant, this would not affect the results. If the crop $k \in \mathcal{K}^c$ is planted on the parcel ω, the production is given by

$$Q_i^{fk}(\omega) = \left[\left(A_i^{fk}(\omega)\, L_i^{fk}(\omega)\right)^{(\eta-1)/\eta} + \left(A_i^{Nk} N_i^{fk}(\omega)\right)^{(\eta-1)/\eta}\right]^{\eta/(\eta-1)}, \tag{11}$$

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 more homogeneity.

I assume that the production of grass does not require any labor. This assumption makes grass the default choice when the productivity of the other crops is not high enough and the corresponding labor costs are too high for growing them. This is consistent with the fact that pastures are more likely to be located on lands that are not the most suitable for crop production because of short growing seasons, limited water access or steep slope. However, this assumption neglects the fact that pastures and hay fields are actively managed and are not simply rangelands. This problem is related to data availability. Agricultural statistics usually have a hard time distinguishing rangelands, pastures, and hay fields, as they concern similar plants along a continuum of management practices, so little information would be available to make the distinction in the model.[3]

In this model, the aggregate supply elasticity of the agricultural sector (similar to the one represented in sections 2.1 and 2.2) is represented by the possibility to intensify production through the use of additional labor and is controlled by η. An alternative would be to introduce an extensive margin of land, allowing agricultural land to expand over other land uses (e.g., forests). To be consistent with the Ricardian approach, this extensive margin is neglected here. The Ricardian

[3] Since grass production does not require any labor, it can increase only by pulling 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 Ricardian approach.

approach focuses on the effect of climate change on the agricultural sector. Thus, it neglects this extensive margin which would require information about the effect of climate change on the other land-using sectors.[4] This implies that there is no need for representing other land uses in the model because the surface of each field s_i^f is restricted to its surface initially used for growing crops or for pastures.

Livestock Livestock products are produced by combining feed and labor:

$$Q_i^{\mathrm{l}} = \min\left(\frac{x_i}{\mu_i}, \frac{N_i^{\mathrm{l}}}{\nu_i^{\mathrm{l}}}\right), \tag{12}$$

where x_i is the demand for feed, the 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 in production, and ν_i^l is the unit-labor requirement in livestock production.

The animal feed is produced competitively from a combination of the various crops that can be used to feed animals. The animal feed itself is not internationally traded, but its production can be made from imported crops. The composition of the feed mix depends on the country-specific composition of the livestock bundle, the animals' physiological requirements (for example the protein/fat/carbohydrate content), the local environment (temperature, humidity, public policies on manure), and the local rearing practices. Accounting for these constraints, producers of feed mix minimize their production costs that are a function of crop prices and quantities. To represent these unobservable elements, the feed mix technology takes a CES form:

$$x_i = \left[\sum_{k\in\mathcal{K}^c} \left(\beta_i^{k,\mathrm{feed}}\right)^{1/\varsigma} \left(x_i^k\right)^{(\varsigma-1)/\varsigma}\right]^{\varsigma/(\varsigma-1)}, \tag{13}$$

where $\varsigma > 0$ and $\neq 1$ is the elasticity of substitution between the various feed crops and $\beta_i^{k,\mathrm{feed}} \geq 0$ is an exogenous technological parameter. For the model version using 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, given by equation (10).

Market structure and trade costs All markets are perfectly competitive. Domestic trade costs are neglected and all producers in a region receive the same price for a crop. This is also the case for grass, which is only assumed 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.

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

$$p_{ij}^k = \tau_{ij}^k p_i^k \text{ for all } k \in \mathcal{K}^a, \tag{14}$$

where p_i^k is the producer price of gook k in region i and p_{ij}^k is its import price in region j.

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

$$p_{ij}^k = p_i^k = p_j^k \text{ for all } k \in \mathcal{K}^a. \tag{15}$$

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

3.2 Equilibrium equations

Good demand Given the 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:

$$C_j = \beta_j P_j^{-\epsilon}, \tag{16}$$

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

$$P_j = \left[\sum_{k \in \mathcal{K}^a} \beta_j^k \left(P_j^k \right)^{1-\kappa} \right]^{1/(1-\kappa)}, \tag{17}$$

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

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

$$C_j^k = \beta_j^k \left(\frac{P_j^k}{P_j} \right)^{-\kappa} C_j. \tag{18}$$

Production Zero profit, absence of trade barriers, and the numeraire assumption in the non-agricultural sector imply $w_i = A_i^0$, which will be used below to substitute w_i away.

From equations (12) and (13), cost minimization in the livestock feed sector implies for $k \in \mathcal{K}^c$:

$$p_i^{\mathrm{l}} = \nu_i^{\mathrm{l}} A_i^0 + \mu_i P_i^{\mathrm{feed}}, \tag{19}$$

$$x_i^k = \beta_i^{k,\mathrm{feed}} \left(\frac{P_i^k}{P_i^{\mathrm{feed}}} \right)^{-\varsigma} \mu_i Q_i^{\mathrm{l}}, \tag{20}$$

$$P_i^{\mathrm{feed}} = \left[\sum_{k \in \mathcal{K}^c} \beta_i^{k,\mathrm{feed}} \left(P_i^k \right)^{1-\varsigma} \right]^{1/(1-\varsigma)}, \tag{21}$$

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

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

$$p_i^k = \left[\left(r_i^{fk}(\omega) / A_i^{fk}(\omega) \right)^{1-\eta} + \left(w_i / A_i^{Nk} \right)^{1-\eta} \right]^{1/(1-\eta)}, \tag{22}$$

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:

$$R_i^{fk}(\omega) = p_i^k Q_i^{fk}(\omega) - w N_i^{fk}(\omega) = r_i^{fk}(\omega) L_i^{fk}(\omega). \tag{23}$$

Defining

$$r_i^k \equiv \left[\left(p_i^k \right)^{1-\eta} - \left(A_i^0 / A_i^{Nk} \right)^{1-\eta} \right]^{1/(1-\eta)}, \tag{24}$$

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

$$R_i^{fk}(\omega) = A_i^{fk}(\omega) L_i^{fk}(\omega) r_i^k. \tag{25}$$

To maximize its profit, the landowner plants a parcel with the crop delivering the highest land rents, $R_i^k(\omega)$. Given that the land rents follow a Type-II extreme value distribution, the acreage choice is a discrete choice problem and the probability that crop k is the most profitable crop is given by

$$\pi_i^{fk} = \frac{\left(r_i^k A_i^{fk}\right)^\theta}{\sum_{l \in \mathcal{K}^c} \left(r_i^l A_i^{fl}\right)^\theta}, \tag{26}$$

where $r_i^k A_i^{fk}(\omega)$ is a measure of the unconditional land rents. Since on each field there is 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, total output of crop k by field f is given by

$$Q_i^{fk} = s_i^f A_i^{fk} \left(\pi_i^{fk}\right)^{(\theta-1)/\theta} \left(\frac{r_i^k}{p_i^k}\right)^\eta. \tag{27}$$

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

$$y_i^{fk} = A_i^{fk} \left(\pi_i^{fk}\right)^{-1/\theta} \left(\frac{r_i^k}{p_i^k}\right)^\eta, \tag{28}$$

which include two components: 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 will be calibrated on potential yields information from the GAEZ project (IIASA/FAO, 2012) and will be shocked to represent the effect of climate change.

From equation (27), country-level production is obtained by summing over all fields:

$$Q_i^k = \left(\frac{r_i^k}{p_i^k}\right)^\eta \sum_{f \in \mathcal{F}_i} s_i^f A_i^{fk} \left(\pi_i^{fk}\right)^{(\theta-1)/\theta}, \tag{29}$$

and total land rents:

$$R_i^k = \left(p_i^k\right)^\eta \left(r_i^k\right)^{1-\eta} Q_i^k = r_i^k \sum_{f \in \mathcal{F}_i} s_i^f A_i^{fk} \left(\pi_i^{fk}\right)^{(\theta-1)/\theta}. \tag{30}$$

Under the Armington assumption, a crop k that is produced under current climate in a country i is always produced under climate change in this country as long as there exists a field $f \in \mathcal{F}_i$ with strictly positive potential yields, $A_i^{fk} > 0$. This comes from the imperfect substitutability of crops from countries of different origins. This is not the case under the integrated world markets assumption. In this case, 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 under which equation (24) would no longer be valid. To account for this possibility, equation (24) is implemented as a complementary slackness condition:

$$r_i^k \geq 0 \quad \perp \quad \left(r_i^k\right)^{1-\eta} \geq \left(p_i^k\right)^{1-\eta} - \left(A_i^0/A_i^{Nk}\right)^{1-\eta}, \tag{31}$$

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

International trade and market clearing Under the Armington assumption, preferences over the countries of origin have been assumed similar for final consumption and for livestock feed, so based on equation (10), the index price that aggregates the price of varieties from various origins is

$$P_j^k = \left[\sum_{i \in \mathcal{I}} \beta_{ij}^k \left(\tau_{ij}^k p_i^k\right)^{1-\sigma}\right]^{1/(1-\sigma)} \quad \text{for all } k \in \mathcal{K}^a, \tag{32}$$

and total import demand is equal to the sum of demand for final consumption and for livestock feed, if relevant:

$$X_j^k / P_j^k = C_j^k + \mathbf{1}_{k \in \mathcal{K}^c} \left(x_j^k\right) \text{ for all } k \in \mathcal{K}^a, \tag{33}$$

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

$$X_{ij}^k = \beta_{ij}^k \left(\frac{\tau_{ij}^k p_i^k}{P_j^k}\right)^{1-\sigma} X_j^k. \tag{34}$$

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

$$p_i^k Q_i^k = \sum_{j \in \mathcal{I}} X_{ij}^k. \tag{35}$$

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

$$P_i^k = p_i^k = p^k \text{ for all } k \in \mathcal{K}^a, \tag{36}$$

and market clearing takes place on the world market:

$$\sum_{i \in \mathcal{I}} Q_i^k = \sum_{i \in \mathcal{I}} \left[C_i^k + \mathbf{1}_{k \in \mathcal{K}^c} \left(x_i^k\right)\right] \text{ for all } k \in \mathcal{K}^a, \tag{37}$$

except for grass:

$$Q_i^g = x_i^g, \tag{38}$$

but its domestic price will be pinned down implicitly by the world price of livestock products through equations (19) and (21).

Competitive equilibrium From the above I can define the competitive equilibrium as follows

Definition 1. A competitive equilibrium under the Armington assumption is a vector of consumption of the bundle of agricultural goods (C_i), price of the bundle of agricultural goods (P_i), final consumption of agricultural goods (C_i^k), production (Q_i^k), feed demand (x_i^k), aggregate feed price (P_i^{feed}), price index of land rents (r_i^k), acreage share (π_i^{fk}), consumption price (P_i^k), total imports (X_i^k), bilateral exports (X_{ij}^k), and producer price (p_i^k) such that equations (16)–(18), (19)–(21), (24), (26), (29), and (32)–(35) hold.

And similarly for the integrated world markets case

Definition 2. A competitive equilibrium with integrated world markets is a vector of consumption of the bundle of agricultural goods (C_i), price of the bundle of agricultural goods (P_i), final consumption of agricultural goods (C_i^k), production (Q_i^k), feed demand (x_i^k), aggregate feed price (P_i^{feed}), price index of land rents (r_i^k), acreage share (π_i^{fk}), price (p^k), and price of grass (p_i^g) such that equations (16)–(18), (19)–(21), (26), (29), (31), and (36)–(38) hold.

3.3 Welfare measures

I introduce below three measures of welfare changes after 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 Ricardian counterpart is denoted v^*. I note also $\hat{v} \equiv v'/v$, the relative changes of 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

$$e\left(P_j^0, P_j, U_j\right) = P_j^0 U_j + \beta_j \left(P_j^0\right)^{\epsilon} \begin{cases} P_j^{1-\epsilon}/(1-\epsilon) & \text{if } \epsilon \neq 1, \\ [1 - \ln(\beta_j P_j^0 / P_j)] & \text{if } \epsilon = 1, \end{cases} \tag{39}$$

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

$$\Delta W_j = R_j \left(\hat{R}_j - 1\right) - P_j C_j \begin{cases} (\hat{P}_j^{1-\epsilon} - 1)/(1-\epsilon) & \text{if } \epsilon \neq 1, \\ \ln \hat{P}_j & \text{if } \epsilon = 1, \end{cases} \tag{40}$$

where $R_j = \sum_{k \in \mathcal{K}^c} R_j^k$ are the total land rents.[5]

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

Ricardian approach Under the Ricardian approach, welfare change is measured by the change in land rents caused by the productivity change associated with climate change but assuming constant prices:

$$\Delta W_j^* = \sum_{k \in \mathcal{K}^c} R_j^{k*} - R_j^k. \tag{41}$$

From equation (40), it can be noted that this is also a valid welfare measure in this model under the assumption of constant prices. If prices are constant, consumer surplus is constant and drops from equation (40), and changes in land rents are the same as under the Ricardian approach.

In this setting, the price index of land rents, r_j^k, remains constant given that it is only function of crop prices, which are assumed constant. In consequence, the Ricardian counterfactual share of land planted with crop k would be

$$\pi_j^{fk*} = \frac{\left(r_j^k A_j^{fk\prime}\right)^{\theta}}{\sum_{l \in \mathcal{K}^c, r_j^l \geq 0} \left(r_j^l A_j^{fl\prime}\right)^{\theta}}. \tag{42}$$

[5] 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 houdehold'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 equation of budget constraint, $E_j = A_j^0 N_j + R_j + \Delta_j$ 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 (16) 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 (40). The same steps apply if $\epsilon = 1$.

It follows that the counterfactual Ricardian land rents are

$$R_j^{k*} = r_j^k \sum_{f \in \mathcal{F}_j} s_j^f A_j^{fk'} \left(\pi_j^{fk*}\right)^{(\theta-1)/\theta}, \tag{43}$$

from which the expression of the Ricardian welfare changes can be derived:

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

In this model, the labor demand for crop production is given by $N_i^k = (A_i^{Nk})^{\eta-1} Q_i^k (p_i^k/w_i)^\eta$. So, under the assumption of constant prices of the Ricardian approach, labor demand will evolve proportionally to production as if the production function was Leontief and the elasticity of substitution, η, should not play a role in Ricardian welfare changes.

Ricardian welfare change can be expressed differently by combining two interesting measures:

$$\delta_j^* = \frac{\sum_{f \in \mathcal{F}_j, k \in \mathcal{K}^c} s_j^f r_j^k A_j^{fk'} \left(\pi_j^{fk*}\right)^{(\theta-1)/\theta}}{R_j} \tag{45}$$

the size of the country-level shock calculated after acreages adjustments but under constant prices (and using land rents as weight) and the total land rents, which determines the potential importance of the agricultural sector in a country. δ_j^* is analogous to the shock to the intercept of the supply curve in sections 2.1 and 2.2.

Production function approach To help with results interpretation, I introduce a third measure of welfare called production function approach. This approach predates the Ricardian approach, which criticized it calling it the "dumb farmer scenario" (Mendelsohn et al., 1994). It neglects both price changes and land re-allocations. It can be derived from the following two steps. First, use a crop model or a statistical model to derive the effect of climate change on yields. Second, combine these yield changes with a measure of the economic importance of each crop to calculate the economic impact of climate change and consider this as a welfare measure.[6]

I follow this logic here but derive a measure consistent with the model. Following what was done before in the Ricardian approach, welfare change in the production function approach is the change in land rents assuming that acreages stay the same:

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

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

There are two things to note about this welfare measure. First, it is exactly the productivity term in a first-order approximation of the true welfare changes in equation (40) (see Gouel and Laborde, 2018, Section 3.4), the other term in the decomposition corresponding to the terms of trade. Second, as for the Ricardian welfare measure, it can be obtained by combining

$$\delta_j = \frac{\sum_{f \in \mathcal{F}_j, k \in \mathcal{K}^c} s_j^f r_j^k A_j^{fk} \left(\pi_j^{fk}\right)^{(\theta-1)/\theta} \hat{A}_j^{fk}}{R_j}, \tag{47}$$

the size of the country-level shock calculated under the assumption of no adjustment (and using land rents as weight)

[6] To be complete and cover all the approaches used historically to assess the welfare effect of climate change in agriculture, a fourth measure of welfare could be introduced to represent the measures obtained from traditional CGE models. These models have usually presented 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 the Table 5 (column 4) of Gouel and Laborde (2018). It shows that neglecting the possible within-country re-allocations severely biases the results.

and the total land rents.

An alternative would be to weight in equation (47) each shock by the contribution of the field to the country value of production. However, in general equilibrium that would be a valid measure only in short run. In the long-run approach adopted here, the factors that are not sector-specific will be reallocated to other uses.

4 Calibration and counterfactual scenario

The calibration of the model follows closely Gouel and Laborde (2018). The information necessary to calibrate the model is identified by expressing the model in changes relative to the equilibrium under current climate (Appendix B.1). I separate the required information into the behavioral parameters that defines the behavior given the initial equilibrium and the data that defines the initial equilibrium. Behavioral parameter values are taken from the literature. The values and sources of parameters and data are indicated in table 3.

Table 3: Parameterization

Parameter	Economic interpretation	Target/Source
Behavioral parameters		
$\epsilon = 0.5$	Elasticity of food demand	Comin et al. (2019)
$\kappa = 0.6$	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 US maize and soybean (Miao et al., 2016)
Initial equilibrium		
A_i^{fk}	Land productivity shifter	Potential yields from the GAEZ project (IIASA/FAO, 2012)
$p_i^k Q_i^k$	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 (30) using A_i^{fk} and R_i^k as observables
π_i^{fk}	Land-use shares	From equation (26)

4.1 Behavioral parameters

The parameter ϵ determines the elasticity of demand for the food bundle. Based on the estimate of Comin et al. (2019), and more generally the structural change literature, a reasonable value for that elasticity is 0.5.

For the elasticity of substitution between food products, we rely on the literature estimating food demand elasticities. Demand elasticities for food products have been studied a lot with typical elasticities below 1 in absolute values and between 0.3 and 0.8 (Andreyeva et al., 2010; Muhammad et al., 2011; Chen et al., 2016). Targeting the typical elasticity in this literature leads to an elasticity of substitution close to 0.6, adopted here. However, most of this literature is concerned with final goods and not primary products as represented in the model. A higher substitution elasticity could be expected between some of the products here, for example cereals, but not between all products given how different they are (consider for example vegetables and cereals or stimulants — cocoa, coffee, and tea — and livestock products).

There is a limited and dated literature on feed demand elasticities pointing to a more elastic demand than the demand for food. Based on Rude and Meilke (2000), I calibrate the substitution elasticity between crops for livestock feed, ς, at 0.9.

The Armington elasticity, σ, is taken equal to 5.4 from the recent estimate of 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 key for achieving current yields, whether current inputs use and yields react much to price changes is open to question. This empirical issue was at the center of the debate about the indirect land use change effect of biofuel policies. Analyzing yield and fertilizer response 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 from section 2.1 this is an assumption favoring the Ricardian approach which also neglects such reactions.

The shape of the Fréchet distribution, θ, is set equal to 1.1 by targeting supply elasticities for US maize and soybean of 0.4, a value typical of the literature (Miao et al., 2016).

4.2 Initial equilibrium

The initial equilibrium is constructed from information about production, consumption, and trade flows in 2011. I discretize the world into $1^\circ \times 1^\circ$ cells, keeping only cells with some agricultural land use in 2011 (Ramankutty and Foley, 1999). Based on its location, each cell is associated to a country or split between several countries if relevant. This results in 11,801 fields. Fifty countries are represented in the model, nine of them corresponding to regional aggregates of several countries (see table A1 for details). Thirty five crops are represented (table A2), all the crops with available information about both potential yield, supply and use. The crop coverage is large enough that it is assumed they use all agricultural land.

Land productivity shifter To each field is associated potential yields for all crops. The potential yields are aggregated at the 1-degree level from the 5-arcminute information provided in the GAEZ project (IIASA/FAO, 2012). As demonstrated in Appendix B.2, the land productivity shifter, A_i^{fk}, can be set equal to the potential yield information. Potential yields are obtained under high inputs and rain-fed assumptions.

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

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

Trade values for crops are taken from FAOSTAT, using by default the importer declaration if available. Trade values for livestock products are taken from GTAP. Both sources are based on COMTRADE, but aggregated to the appropriate product level.

The values of crops used for livestock feed are calculated using FAOSTAT commodity balances. The commodity balances provide information about the various sources of supply (production, imports and stocks) and the various uses.

From the commodity balance, I calculate the share of feed in total supply and multiply it with the value of production plus imports, thus assuming 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 between the various sources (for example between the trade data 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 There is no available dataset allowing to recover the initial land allocation, π_i^{fk}, and the initial price index of land rents, r_i^k, but they can be recovered from the optimality conditions of the land owner problem and the other observables. Indeed, 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 (30) (see Gouel and Laborde, 2018, Appendix A for a proof). Using the r_i^k, the initial land allocation can then be calculated using equation (26).

4.3 Climate change counterfactual

Once the model is calibrated and replicate the equilibrium under current climate, current trade imbalances are removed. Given the model structure, this does not affect the equilibrium on the agricultural markets but only the GDP that is used to normalize the welfare results. The model is then used to simulate the effects of climate change on agriculture by changing the value of potential yields to values provided by the GAEZ project at the 2080s horizon under the emission scenario A1FI. The new equilibrium is found by solving the model's equations, expressed in deviation from the benchmark equilibrium in Appendix B.1, using modeling language GAMS and the PATH solver to account for the complementary equation (31).

5 Results

5.1 Main welfare results

This section discusses the main welfare results obtained by solving the model after changing the potential yields, A_i^{fk}, from their values under current climate to values under climate change. Table 1 presents the main results. Column 1 reports the value of net agricultural trade (exports minus imports) as a share of the value of agricultural production. This measure will prove useful as a predictor of the direction of the bias of the Ricardian approach related to terms-of-trade effects. Column 2 reports the share of land rents with respect to GDP. Land rents are an important measure because, by construction, the production function and the Ricardian 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 weight and assuming, respectively, no adaptation and adaptation through acreage changes at constant prices. Multiplying columns 2 and 3 gives column 5, the production function approach welfare change. Multiplying columns 2 and 4 gives column 6, the Ricardian approach welfare change. Column 7 reports the exact welfare changes and column 8 the relative bias of the Ricardian approach. All welfare changes are expressed in percentage of GDP (GDP once trade deficits have been removed).

An insight of the Ricardian approach was that accounting for adaptation through the land market was important because the "dumb farmer" assumption of the production function approach was leading to excessive welfare losses. This is confirmed in table 4 where column 6 is always superior or equal to column 5. Things are different when accounting for additional adaptation through the crop and land markets. In this case, the bias can go in both directions, but more often than not it is negative (for 38 countries out of 50), with true welfare changes lower than the Ricardian changes. A good predictor of the sign of the bias is the sign of the agricultural trade in column 1. All net importers have a negative bias, and 12 net exporters over 19 have a positive bias. The 7 net exporters with a negative bias have either

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)	Ricardian (6)	Exact (7)	$\text{Bias}_j/\Delta W_j$ (%) (8)
Argentina	60.64	1.24	13.85	20.16	0.17	0.25	3.47	92.79
Australia	34.72	0.28	−28.96	−27.22	−0.08	−0.08	0.26	129.74
Bangladesh	−31.46	3.17	−21.87	−21.22	−0.69	−0.67	−9.31	92.77
Brazil	38.01	0.67	−44.20	−41.96	−0.29	−0.28	0.92	130.49
Canada	25.38	0.16	44.28	103.18	0.07	0.16	0.06	−153.62
China (including Hong Kong)	−4.96	1.95	−0.04	49.37	−0.00	0.96	−0.65	247.39
Colombia	4.46	1.24	−46.62	−41.75	−0.58	−0.52	−1.72	69.99
Egypt	−48.13	0.47	24.22	28.60	0.11	0.13	−4.18	103.22
Ethiopia	0.66	4.79	3.67	18.14	0.18	0.87	15.73	94.48
France	17.65	0.19	−25.70	−21.20	−0.05	−0.04	0.06	165.70
Germany	−6.76	0.16	4.49	9.30	0.01	0.01	−0.73	102.04
Greece	−9.92	0.81	−43.45	−38.45	−0.35	−0.31	−7.74	95.99
India	4.78	4.72	−10.66	−8.76	−0.50	−0.41	−7.48	94.47
Indonesia	−7.88	4.87	−23.47	−22.15	−1.14	−1.08	−4.94	78.17
Iran	−14.54	0.42	−36.82	−34.19	−0.15	−0.14	−2.20	93.51
Italy	−23.40	0.22	−33.74	−30.72	−0.07	−0.07	−1.88	96.46
Japan	−31.66	0.18	12.36	30.34	0.02	0.05	−0.43	112.67
Kazakhstan	−1.12	0.61	13.05	27.30	0.08	0.17	−1.08	115.49
Kenya	4.81	1.29	2.94	30.93	0.04	0.40	9.41	95.76
Korea, South	−48.81	0.53	11.56	118.59	0.06	0.63	−0.97	165.66
Malaysia	−30.10	2.72	−7.32	−6.99	−0.20	−0.19	−5.46	96.52
Mexico	−17.17	0.46	−38.58	−34.94	−0.18	−0.16	−0.61	73.64
Morocco	−27.36	0.80	−61.89	−61.30	−0.49	−0.49	−7.74	93.69
Netherlands	−16.07	0.12	−6.79	−5.03	−0.01	−0.01	−3.33	99.82
Nigeria	−9.98	1.36	−46.67	−44.96	−0.63	−0.61	−14.59	95.81
Pakistan	1.86	3.07	−17.29	−6.14	−0.53	−0.19	−1.46	87.06
Peru	−6.52	1.21	35.33	41.23	0.43	0.50	−1.18	142.32
Philippines	−0.76	3.19	−33.52	−32.11	−1.07	−1.02	−1.45	29.38
Poland	2.37	0.83	10.57	12.22	0.09	0.10	−0.32	131.92
Romania	−1.96	1.82	−14.75	−14.58	−0.27	−0.27	−1.07	75.22
Russia	−9.17	0.54	−3.29	5.87	−0.02	0.03	−0.73	104.36
Senegal	−45.21	1.23	−72.91	−72.11	−0.89	−0.88	−11.71	92.45
South Africa	1.43	0.21	−41.43	−39.29	−0.09	−0.08	0.40	120.82
Spain	1.11	0.20	−41.02	−35.97	−0.08	−0.07	−0.02	−321.17
Sri Lanka	−38.64	1.90	−33.04	−31.47	−0.63	−0.60	−9.81	93.90
Thailand	20.56	2.50	−37.16	−36.13	−0.93	−0.90	−4.06	77.73
Turkey	−7.26	0.47	−18.18	−0.96	−0.09	−0.00	−0.68	99.34
Ukraine	30.53	1.82	−12.25	−11.80	−0.22	−0.21	1.18	118.13
United Kingdom	−38.73	0.14	5.97	11.90	0.01	0.02	−0.52	103.28
United States	15.24	0.26	−20.23	−11.14	−0.05	−0.03	−0.19	84.39
Viet Nam	−1.74	6.56	−32.22	−30.41	−2.11	−2.00	−7.23	72.39
Asia	−5.93	1.82	−8.84	15.90	−0.16	0.29	−1.73	116.74
CIS[b]	−1.68	0.77	−2.76	9.84	−0.02	0.08	−0.70	110.76
Europe	−5.15	0.25	−10.67	0.04	−0.03	0.00	−0.80	100.01
Latin America	23.86	0.80	−34.47	−31.12	−0.28	−0.25	0.18	237.45
Middle East and North Africa	−38.46	0.29	−26.01	−19.17	−0.08	−0.06	−2.41	97.66
Northern America	16.47	0.25	−16.06	−3.75	−0.04	−0.01	−0.16	94.15
Oceania	37.30	0.35	−20.91	−18.55	−0.07	−0.06	0.23	127.62
Sub-Saharan Africa	−3.09	1.38	−39.87	−35.81	−0.55	−0.49	−6.58	92.49
World	0	0.78	−13.18	5.77	−0.10	0.04	−1.00	104.47

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.

a trade position close to 0 (e.g., Pakistan) or a climate change shock large enough to change their trade status (e.g., Thailand). From these results, and consistently with the insights from section 2.2, it can be expected that terms-of-trade effects are a strong driver of the sign of the bias of the Ricardian approach.[7]

Terms-of-trade effects cancel at the world level, but the bias does not: the true global welfare change is a welfare loss of 1% while the Ricardian welfare change is a 0.04% gain. As predicted by the example in section 2.3, in the absence of terms-of-trade effect and if the bias is caused by the imperfect substitutability of crops, true welfare should be inferior to Ricardian welfare, a situation confirmed at the world level for all the parameter variations considered in the next section and in Appendix D.

As previously mentioned, the welfare changes under the Ricardian approach are superior to the welfare changes under the production function approach, but they tend to have 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 with indexes of production change (δ_j and δ_j^*), so examining the values of these indexes will explain the differences between columns 5 and 6. Since the only difference between columns 3 and 4 is the acreage adjustments incentivized by relative yield changes, the differences between the two columns are due to the between-crop heterogeneity of the climate shock. If the shock is uniform across crops, acreages do not adjust and $\delta_j = \delta_j^*$. It is the case for many countries. But there are a few countries with sizable differences, typically countries located in Southern and Northern latitudes (e.g., Argentina, Canada, China, Germany, Japan, Korea, and Russia). In these countries with mild climates, some crops well adapted to these climates may have lower yields under climate change, but their overall climate evolves toward one more adapted to growing crops, hence the heterogeneous yield shock. Finally, the Ricardian and production function welfare changes have a different order of magnitude than true welfare change, because they cannot account for the possibility that food may become scarcer under climate change, which would make land more valuable and land rents higher. This explains the size of the relative bias in column 8 with typical values around 100, the ones exceeding 100 indicating welfare changes with opposite signs.

Considering the exact welfare changes, some countries present gains from climate change. This can happen under two settings: a country that benefits from climate change in the production function and Ricardian approach or a country that benefits from improving terms of trade, typically an exporting country. The two effects can be combined and reinforce each other, for example in the case of Argentina which benefits from higher yields under climate change but is also an important exporter and benefits from higher export prices. For countries with negative Ricardian welfare changes (e.g., Australia, Brazil, Ukraine), but positive true welfare changes, terms-of-trade effects likely dominate the productivity effects. The opposite happens also with countries presenting welfare gains in the Ricardian approach but negative true welfare changes (e.g., Egypt, Germany, and Korea). In this case, the gains from higher yields are compensated by losses from higher import prices.

5.2 Conditions of validity of the Ricardian approach

This section explores the combinations of assumptions under which the Ricardian approach provides a valid approximation of the true welfare changes. Figure 4 presents the key variations, but additional results are available in figure A1 in appendix, some of them being discussed here. Figure 4 presents scatter plots of Ricardian welfare changes with respect to true welfare changes for the 50 countries in the model and for the world. Each panel corresponds to a different set of model assumptions. A linear regression and its R-squared is reported in each panel, as well as the regression line in blue. Panel 1 reproduces graphically the results of table 4. Panel 2 presents the results when the model is calibrated using Costinot et al. (2016) key elasticities (see section C for more details and discussion). It represents a more elastic calibration than the benchmark, but this does not affect the conclusions drawn previously. With Costinot et al. elasticities, as in the benchmark, several countries present welfare measures with opposite signs (pink points), including the world aggregate (red point). With these more elastic demand and supply schedules, the correlation increases but remains small and the biases large.

[7]The importance of the terms-of-trade effect of climate change is emphasized among others in Gouel and Laborde (2018) and Baldos et al. (2019).

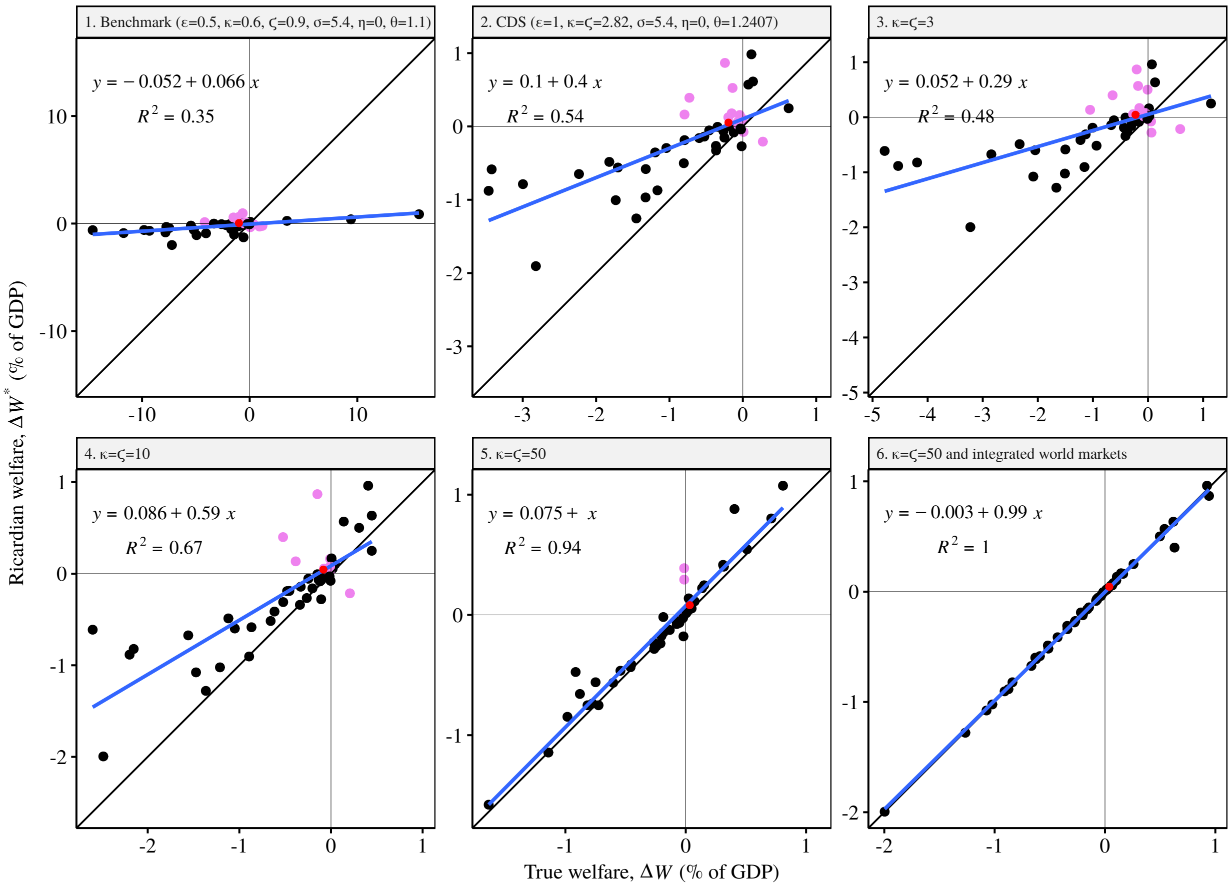


Figure 4: The role of demand substitution and trade costs in the bias of the Ricardian method. Notes: pink points indicate countries for which the Ricardian and exact welfare measures have opposite signs, red points indicate world welfare, and the blue lines are the regression lines also displayed as equations in the top-left part of each panel. Except for panels 1 and 2, panel titles correspond to the assumptions and parameters that are changed, keeping the rest as in the benchmark situation.

For all the model assumptions considered, here and in appendix, Ricardian welfare changes are positively correlated to the true welfare changes, but the correlation is high only for particular combinations of parameters. Ricardian welfare changes are also mostly located above the diagonal lines indicating an underestimation of the welfare cost of climate change. The key parameters appears to be the elasticities of substitution for final and intermediate demand, κ and ς. Panels 3 to 5 increase them to 3, 10, and 50, keeping other parameters at their benchmark values. Increasing κ and ς to 3 (panel 3) brings this dimension of the model close to the situation in panel 2 and explains more than half of the difference between panels 1 and 2 (the rest being mostly explained by the value of ϵ). Increasing these elasticities to 10 (panel 4) increases the R^2 to 0.67, and increasing them further to 50 (panel 5) increases the R^2 to 0.94, a very high but not perfect fit. An almost perfect fit is obtained in panel 6 by assuming in addition integrated world markets for agricultural products (except grass); this neglects trade costs and the imperfect substitution by country of origin of the Armington assumption.

The role of κ can be explained easily from equation (40) and is similar to what was illustrated by 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 heterogeneous enough between crops, which the difference between δ and δ^* at the world level indicates, then the decreased yield of one crop can be compensated by the increased yield of another crop if they substitute enough on the demand side. Since from a Ricardian perspective, the climate change shock is a small positive shock at the world level, with a high enough κ, $\hat{P}_j$ is very close to 1, even more so if trade costs are neglected. For $\hat{P}_j = 1$, there are no changes in consumer surplus caused of climate change, and since relative prices barely change, the Ricardian approach delivers a good approximation of the changes in land rents.

Given that the Ricardian approach neglects changes in consumer surplus and, from equation (40), consumer surplus is a function of ϵ, one could have expected this parameter to play a big role in the bias of the Ricardian method. If we consider 1 to be an upper bound for this parameter because above 1 the budget share of food decreases with a price increase, then its role is actually more nuanced. By construction, ϵ does not affect the Ricardian welfare measure but affects the true welfare measure by scaling the size of the price increase of the agricultural goods bundle. So, it does affect the order of magnitude of the welfare changes. If $\epsilon = 1$, the budget share of agricultural product is constant at constant income, so at constant income the level of land rents should be similar in magnitude to the benchmark. With $\epsilon < 1$, the budget share of agricultural products increases with prices and so does the magnitude of the effect of climate change. However, even though increasing ϵ toward 1 brings the two welfare measures to the same order of magnitudes, panel 12 of figure A1 shows that the correlation between both welfare measures are weakly affected by the increase. At another extreme, increasing ϵ to a value of 100 (results not reported on figure A1) reduces changes in consumer surplus to a very small share of welfare changes, but the correlation between the welfare measures remain small with a R^2 of 0.45, because of the changes in crop relative prices that affect producer surplus and are not accounted for in the Ricardian approach. ϵ plays a role in mediating the effect of κ: a higher ϵ reduces the bias for a given κ, but increasing ϵ alone cannot suppress the bias as increasing κ does.

6 Conclusions

One of the important benefits of the Ricardian method for evaluating the economic impact of climate change on agriculture, and its main appeal, is its simplicity. There is no need to combine projections by crop scientists of the effect of climate change on crop yields with an equilibrium model of the global agricultural markets and to estimate the key parameters of this model, a much more complex endeavor than running a cross-sectional regression. However, this paper demonstrates that this simplicity comes at a great cost since this method is likely to be severally biased. Being a reduced-form econometric estimation of how farmland rents evolve with climate, it focuses on the equilibrium on the market for agricultural land while neglecting the equilibrium on the crop market at the domestic and international levels.

Using simple textbook examples, I show that the Ricardian approach should in average underestimate, possibly by large, the true welfare losses from climate change because it neglects the imperfect substitutability of crops in demand. In addition, by neglecting the transfers created by terms-of-trade changes between countries, the Ricardian approach could overestimate the losses from climate change for net food exporting countries, which may benefit from higher export prices. I confirm these findings using a parsimonious quantitative trade model of global agricultural markets that encompasses these various mechanisms and is able to emulate the findings of a Ricardian approach as well as to calculate exact welfare changes. Comparing both welfare measures shows that, under calibrations consistent with the literature, they have a small correlation and are potentially of different signs. The Ricardian 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 as is done in the Ricardian approach.

The results in this paper point to the need to reorient the research priorities in the evaluation of the effects of climate change in agriculture toward work complementary to equilibrium models. First, it could be toward the sensitivity of yields to climate. One of the key insights of Mendelsohn et al. (1994) was that the approaches relying on a production function logic, in addition to their bias, were focusing too much on the main crops (i.e., maize, rice, soybean, and wheat) and neglecting that lower yields for these crops under a warmer climate could be compensated by higher yields for specialty crops. This focus on the main crops is still the case in most of the literature assessing the effects of climate change on yields (e.g., Moore et al., 2017; Schlenker and Roberts, 2009; Burke and Emerick, 2016). The GAEZ database we have relied on in this study is an exception since it provides potential yields for all sorts of crops, but it is now dated (IIASA/FAO, 2012) and does not provide potential yields for the most recent scenarios of greenhouse gas concentration (the Representative Concentration Pathways).

Second, it could be toward the estimation of the key elasticities in the sector. For parsimony, this model assumes the same elasticities for all countries, crops, and fields, which is unlikely to be valid. While this assumption does not matter for the objective of the paper, it will for a specific focus on the welfare cost of climate change. Recent works on the Ricardian approach have emphasized the importance of using farm-level data rather aggregated data such as county-level data (Fezzi and Bateman, 2015; Passel et al., 2017). Another use of these farm-level data would be the estimation of production functions as well the degree of substitution of land to plant different crops.

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 one, consumption and productivity shifters can be related to 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 Ricardian approach is 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:

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

Using that initial prices are taken to be 1 gives

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

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

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

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

To calculate true welfare changes from climate change, let 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 we can derive the counterfactual quantities:

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

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's equations in relative changes. This change makes explicit the data necessary for 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. Finally, $\phi_i^{k,\text{labor}}$, $\phi_i^{k,\text{land}}$, 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 but positive yields under climate change, a situation under which $\hat{\pi}_i^{fk}$ 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 if it was not produced under 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 precised, the following equations hold for all $i, j \in \mathcal{I}$, $k \in \mathcal{K}$:

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

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

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

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

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

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

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 assumptions includes the following ones:

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

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

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

In previous equations, excluding the behavioral parameters, all the parameters are directly observable in the data, except for the initial values of r_i^k and π_i^{fk}. Gouel and Laborde (2018, Section 2.3) show that equation (30) 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 (26).

B.2 Calibration of the land productivity shifter

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

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

So, $A_i^{f\,k}$ equals GAEZ potential yields, except for a country-crop productivity shifter $(r_i^{k,G}/p_i^{k,G})^{\eta}$. One interesting property of this model (see Gouel and Laborde, 2018, 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. It means that for simplicity, we can take $A_i^{f\,k} = y_i^{f\,k,G}$.

This approach presents one limit in the context of climate change. We have to assume that the same set of prices that rationalizes the assumptions about input levels used for current climate is also used in the construction of GAEZ potential yields under climate change. This seems to be consistent with the GAEZ definition of high level inputs as the yields under "optimum applications of nutrients and chemical pest, disease and weed control" (IIASA/FAO, 2012), but it cannot be completely excluded that some farm-level adaptations about input uses are embedded in these potential yields under climate change.

B.3 Country and sector mappings

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

C Results using Costinot et al. (2016) parameters

At the time of this writing, the text of this appendix is to be completed, but results are available in table A3.

Table A3: Welfare results using Costinot et al. (2016) parameters ($\epsilon = 1, \kappa = \varsigma = 2.82, \sigma = 5.4, \eta = 0, \theta = 1.2407$)

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)	Ricardian (6)	Exact (7)	$\text{Bias}_j / \Delta W_j$ (%) (8)
Argentina	60.64	1.24	13.78	20.03	0.17	0.25	0.62	60.24
Australia	34.72	0.28	−28.84	−26.26	−0.08	−0.07	0.01	928.45
Bangladesh	−31.46	3.17	−21.90	−20.45	−0.69	−0.65	−2.23	70.95
Brazil	38.01	0.67	−44.58	−40.64	−0.30	−0.27	−0.02	−1565.38
Canada	25.38	0.16	43.72	99.47	0.07	0.16	−0.04	468.62
China (including Hong Kong)	−4.96	1.95	−0.04	50.53	−0.00	0.98	0.12	−741.75
Colombia	4.46	1.24	−46.62	−40.51	−0.58	−0.50	−0.80	37.70
Egypt	−48.13	0.47	24.20	34.52	0.11	0.16	−0.80	120.45
Ethiopia	0.66	4.79	1.62	18.10	0.08	0.87	−0.24	455.02
France	17.65	0.19	−25.79	−21.26	−0.05	−0.04	−0.03	−58.53
Germany	−6.76	0.16	4.35	9.10	0.01	0.01	−0.07	120.06
Greece	−9.92	0.81	−43.54	−36.46	−0.35	−0.29	−1.04	71.78
India	4.78	4.72	−11.04	−7.51	−0.52	−0.35	−1.20	70.34
Indonesia	−7.88	4.87	−23.45	−20.67	−1.14	−1.01	−1.73	41.96
Iran	−14.54	0.42	−36.96	−33.22	−0.15	−0.14	−0.53	73.64
Italy	−23.40	0.22	−33.51	−29.31	−0.07	−0.06	−0.27	76.02
Japan	−31.66	0.18	12.88	30.10	0.02	0.05	−0.02	327.05
Kazakhstan	−1.12	0.61	12.75	29.21	0.08	0.18	−0.15	217.72
Kenya	4.81	1.29	2.00	30.30	0.03	0.39	−0.73	153.67
Korea, South	−48.81	0.53	11.59	114.59	0.06	0.61	0.14	−343.00
Malaysia	−30.10	2.72	−7.35	−6.87	−0.20	−0.19	−0.79	76.52
Mexico	−17.17	0.46	−38.96	−33.29	−0.18	−0.15	−0.25	39.27
Morocco	−27.36	0.80	−61.95	−60.70	−0.49	−0.48	−1.82	73.44
Netherlands	−16.07	0.12	−6.89	−4.74	−0.01	−0.01	−0.34	98.39
Nigeria	−9.98	1.36	−46.91	−43.02	−0.64	−0.59	−3.42	82.91
Pakistan	1.86	3.07	−16.99	−5.16	−0.52	−0.16	−0.59	73.33
Peru	−6.52	1.21	39.41	47.00	0.48	0.57	0.08	−655.96
Philippines	−0.76	3.19	−33.48	−30.40	−1.07	−0.97	−1.33	26.99
Poland	2.37	0.83	10.42	12.38	0.09	0.10	−0.00	3284.38
Romania	−1.96	1.82	−14.83	−14.56	−0.27	−0.27	−0.37	27.59
Russia	−9.17	0.54	−3.81	6.09	−0.02	0.03	−0.09	136.92
Senegal	−45.21	1.23	−73.41	−71.58	−0.90	−0.88	−3.46	74.66
South Africa	1.43	0.21	−41.72	−38.45	−0.09	−0.08	−0.12	33.53
Spain	1.11	0.20	−41.28	−34.97	−0.08	−0.07	−0.12	42.65
Sri Lanka	−38.64	1.90	−33.03	−29.46	−0.63	−0.56	−1.70	67.10
Thailand	20.56	2.50	−37.16	−34.83	−0.93	−0.87	−1.16	25.12
Turkey	−7.26	0.47	−18.18	−0.52	−0.09	−0.00	−0.16	98.49
Ukraine	30.53	1.82	−12.34	−11.42	−0.22	−0.21	0.27	176.06
United Kingdom	−38.73	0.14	5.89	12.08	0.01	0.02	−0.06	127.70
United States	15.24	0.26	−20.48	−10.86	−0.05	−0.03	−0.03	13.01
Viet Nam	−1.74	6.56	−32.26	−29.04	−2.12	−1.90	−2.82	32.48
Asia	−5.93	1.82	−8.87	17.10	−0.16	0.31	−0.24	228.41
CIS[b]	−1.68	0.77	−3.03	9.61	−0.02	0.07	−0.07	198.50
Europe	−5.15	0.25	−10.73	−0.35	−0.03	−0.00	−0.12	99.23
Latin America	23.86	0.80	−34.54	−29.84	−0.28	−0.24	−0.20	−21.39
Middle East and North Africa	−38.46	0.29	−26.07	−18.05	−0.08	−0.05	−0.46	88.56
Northern America	16.47	0.25	−16.33	−3.73	−0.04	−0.01	−0.03	72.21
Oceania	37.30	0.35	−20.69	−17.54	−0.07	−0.06	−0.01	−868.16
Sub-Saharan Africa	−3.09	1.38	−40.35	−34.27	−0.56	−0.47	−2.22	78.65
World	0	0.78	−13.25	6.70	−0.10	0.05	−0.20	126.53

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.

D Additional results on the role of model assumptions

At the time of this writing, the text of this appendix is to be completed, but some results are available in figure A1. The results about the role of η when different from 0 are still to come.

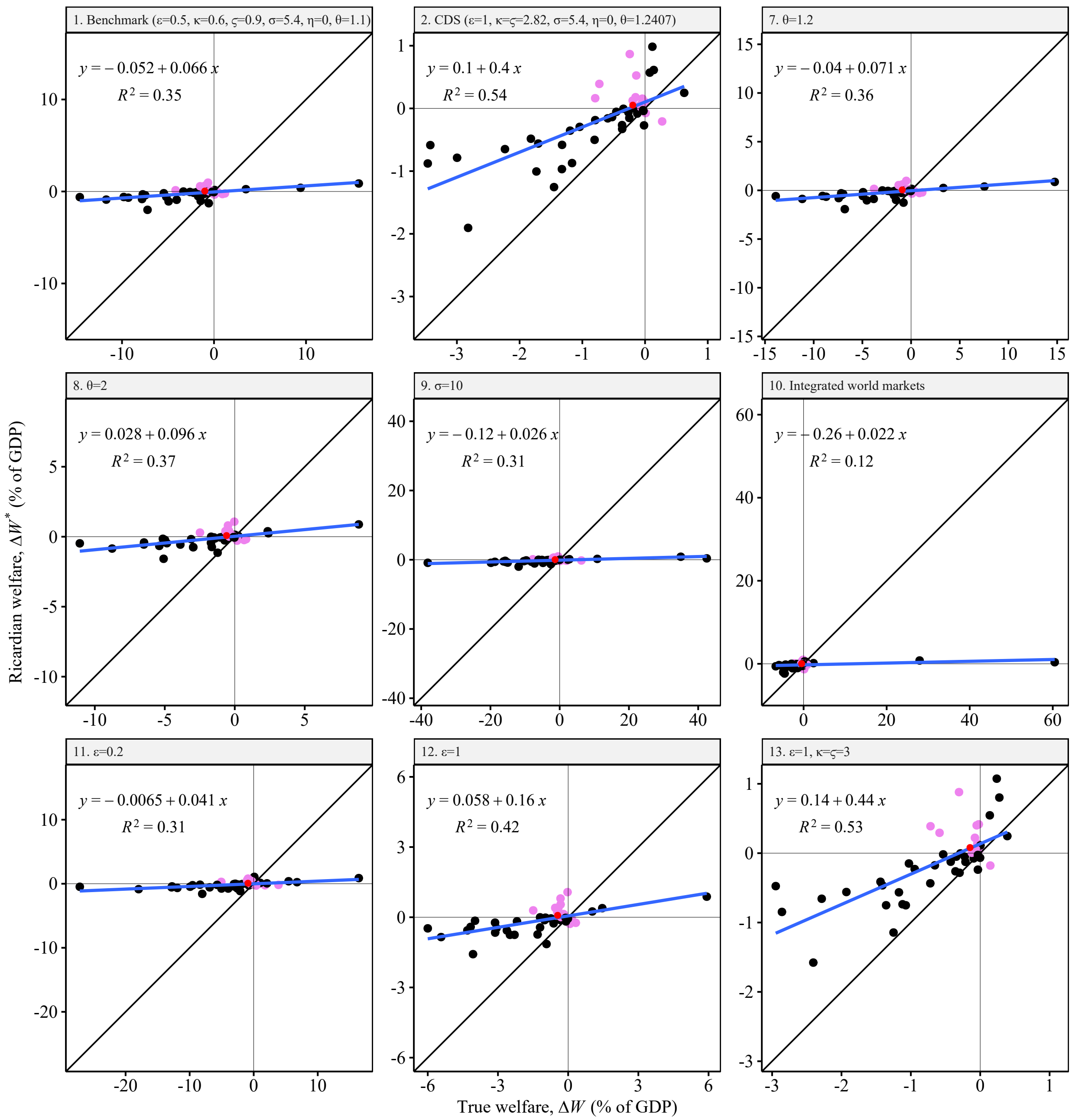


Figure A1: Additional results on the role of model assumptions in the bias of the Ricardian method. Notes: pink points indicate countries for which the Ricardian and exact welfare measures have opposite signs, red points indicate world welfare, and the blue lines are the regression lines also displayed as equations in the top-left part of each panel. Except for panels 1 and 2, panel titles correspond to the assumptions and parameters that are changed, keeping the rest as in at the benchmark situation.

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