The Crucial Role of International Trade in Adaptation to Climate Change*

Christophe Gouel†[1,2] David Laborde‡[2]

[1]Économie Publique, AgroParisTech, INRA, Université Paris-Saclay, 78850, Thiverval-Grignon, France
[2]International Food Policy Research Institute, 1201 Eye St NW, Washington, DC 20005, USA

May 2, 2018

Abstract

Climate change effects on agricultural yields will be uneven over the world with a few countries, mostly in high latitudes, that may experience gains, while most will see average yield decrease. This paper aims at quantifying the role of international trade in attenuating the effects of climate change by allowing the expression of the new climate-induced pattern of comparative advantages. To do this, we develop a new quantitative general equilibrium trade model where the representation of acreage and land use choices is inspired from modern Ricardian trade models but also consistent with theoretical and empirical literature on land use choices. The model is calibrated on spatially explicit information about potential yields before and after climate change coming from the agronomic literature. The results show that, because demand for food is quite inelastic, the climate-induced yield changes generate large price movements that incentivize adjustments in acreage and trade. The new trade pattern is very different from the current one showing the important role of trade flows in adapting to climate change. This is confirmed by large increased welfare losses from climate change when adjustments in trade flows are constrained.

Keywords: agriculture, climate change, international trade, land use.

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

*The authors are grateful to Eddy Bekkers, Antoine Bouët, Alexandre Gohin, Thomas Hertel, Chantal Le Mouël, Will Martin, Obie Porteous, and seminar audiences at the FAO conference on "Climate change, agricultural trade, and food security", 2017 IATRC annual meeting, Middlebury College, North Carolina State University, University of California, Berkeley and Davis, and US International Trade Commission for helpful comments. Christophe Gouel thanks the INRA-Cirad métaprogramme GloFoodS for research support.

†Corresponding author, christophe.gouel@inra.fr

‡d.laborde@cgiar.org

1 Introduction

Climate change will widely impact agriculture, but this impact may be very different between countries. Northern countries with currently cold temperatures and short growing seasons may benefit from higher yields in some crops, while tropical countries may see reduced yields because of extreme temperatures (see table 1 for the extent of region- and crop-specific variations). These differential changes in crop productivity correspond to changes in comparative advantages; therefore, one could expect a large role of international trade to mitigate the negative effects of climate change. The role that international trade may play is, however, a function of the size of the other adjustments, such as the changes in crop choices or demand adjustments. Yield changes will be heterogeneous between countries, but also within countries. Even countries adversely affected in average may have high-altitude areas where the increased temperatures will benefit agriculture production. Reallocating domestic crop production in areas where yields increase may go a long way to attenuating the initial yield loss. Similarly, growing different crops, more adapted to the new climate, may contribute to reduce the adverse effects of climate change if crop demand for feeding livestock can move easily between different crops. If these other margins of adjustments are important enough, the disequilibrium between domestic supplies and demands caused by climate change may be low and the role of international trade to balance it limited.

Table 1: Climate change impacts on crop yields, accounting for carbon dioxide fertilization (percentage change)

Region	Maize	Rice	Wheat	Other crops	All crops
Asia	15.3	3.9	−53.5	−12.8	−8.9
Commonwealth of Independent States	−9.7		−1.5	−2.0	−2.3
Europe	−15.1	51.5	−8.2	−11.6	−11.1
Latin America	3.3	−36.9	−35.3	−38.9	−35.4
Middle East and North Africa	115.5	−87.2	−25.9	−29.1	−23.0
Northern America	−15.7	9.1	−5.1	−18.4	−16.2
Oceania	20.9	−32.4	−40.0	−16.7	−19.8
Sub-Saharan Africa	0.0	−15.3	−76.3	−42.6	−38.7
World	1.5	3.2	−33.3	−17.2	−13.2

Source: GAEZ project (IIASA/FAO, 2012), aggregated by crop and region based on the first-order contribution of each pixel to welfare (see sections 3 and 4 for details).

The objective of this paper is to quantify the contribution of the various margins of adjustment to climate change in agriculture and to understand how they affect the role of international trade, which is on the cusp of the demand and supply adjustments. The question of the role of international trade in climate change adaptation is above all an empirical question, whose answer depends on the flexibility of all the other adjustment margins. However, answering this question requires a theoretical framework that integrates the various margins in a consistent way. This framework is a general equilibrium trade model with a focus on the agricultural sector. The model builds on recent developments in the trade literature on assignment models (Costinot and Vogel, 2015) that have been extended to agricultural settings in Costinot et al. (2016, hereafter CDS) and Sotelo (2015). It uses gridded information from crop science on potential yields under the current climate and under climate change for calibration and counterfactual simulations. Each margin of adjustment is parameterized separately in the model. On the demand side, there are the price elasticity of total agricultural demand and the elasticity of substitution between agricultural products. On the supply side, there are the acreage elasticity, the yield elasticity (in sensitivity analysis), and the elasticity of substitution between agricultural products for livestock feeding. And, in between demand and supply, there is the trade elasticity. We rely on the vast agricultural economics literature devoted to the estimation of supply and demand elasticities to propose a realistic calibration for the model and to assess the uncertainty around these parameters for the sensitivity analysis.

The question of the role of international trade in adaptation to climate change was recently addressed in CDS. Using counterfactual simulations, they show that restricting acreages under climate change to stay the same as current acreages would severely aggravate the impacts of climate change, while forcing the exported share of crops to be the same as without climate change would only have a small effect on welfare. So, they concluded that acreage changes play an important adaptive role, while international trade adjustments play a limited role. This is a surprising result given the very heterogeneous effects of climate change illustrated in table 1. The present paper challenges this conclusion. We show that CDS' conclusion is likely related to a combination on model assumptions and parameters estimation leading to very elastic demand and supply for food, and with potentially large domestic adjustments, trade adjustments play a small role. On the modeling side, they use for demand a functional form implying a unit price elasticity for the food bundle and assume for supply that cropland can be extended over "unused" lands without any other opportunity costs that the production costs, which neglects the fact that land not used for planting crops have valuable uses and will not be converted into cropland without significant costs. For the estimations, they estimate on noisy cross-sectional data a substitution elasticity between primary agricultural products using total demand, which includes intermediate demand for livestock feed and industrial uses that are likely to be more elastic than final demand for food and that are also strongly driven by policies (e.g., biofuels policies on sugarcane in Brazil, vegetable oil in Europe, and maize the U.S.). Their estimated substitution elasticity implies final demand elasticities that are three times higher than usual estimates in the literature. The inelasticity of agricultural good demand is a well-established empirical result (Fally and Sayre, 2017; Roberts and Schlenker, 2013) and a necessary piece to explain the observed large price changes in these markets for apparently small reductions in supply. Similarly, except for the few tropical countries that still have a land frontier, future supply adjustments coming from changes in total agricultural land (cropland plus pasture land) are expected to be marginal (Alexandratos and Bruinsma, 2012). This combination of highly elastic demand and supply that is not supported empirically explains the limited role of international trade in their study. If demand and supply for agricultural goods are very elastic, then a reduction in yields translates into a reduction in final demand and an adjustment in acreages but does not change the relative prices enough to trigger large trade changes.

Our model framework presents the following elements. Three types of goods are represented: crops, livestock, and a non-agricultural product. Though our modeling of livestock is very simple, the inclusion of livestock is crucial for the question at hand through its use of pastures, the single largest human use of land, and through its demand for feed which is likely to be more elastic than food demand and so should constitute a valuable margin of adjustment. The model includes 35 crops and aim to represent all the crops with a significant role in final demand and agricultural land use. Representing almost all crops allows us to make a clear connection with the literature estimating calorie-price elasticities (Subramanian and Deaton, 1996) and makes sure that the opportunity costs of converting land between its various agricultural uses are accounted for. All goods are considered as imperfectly substitutable based on their countries of origin and trade is subject to iceberg trade costs. Our modeling of acreage choice builds on CDS' approach, itself inspired from Eaton and Kortum (2002) modeling of trade in homogeneous goods (an acreage modeling also recently used in Sotelo, 2015). Its key element is to assume that potential yields follow an extreme value distribution, which delivers a simple expression of acreage choice. In our land-use modeling, because we assume no production cost for pasture, pasture can be considered as the default choice for lands where yields of other crops are low compared to their production costs. We do not consider the possibility of extending agricultural land over forest or over protected areas, contrary to CDS because, in addition to the difficulty of modeling properly these decisions (see Scott, 2014, for example), extending agricultural land use would severely aggravate greenhouse gas emissions and climate change.

This paper fits into the recent literature evaluating gains from trade using a large class of models delivering structural gravity equations (Costinot and Rodríguez-Clare, 2014). In this literature, Fally and Sayre (2017) and Farrokhi (2017) show that accounting for the specificities of commodities lead to higher gains from trade. Commodities tend to be produced using sector-specific non-tradable resources (in our case land), they have low supply elasticities, because of their use of specific assets, and they have low demand elasticities, because of their essential role in downstream sectors. These features explain why they could contribute comparatively more to gains from trade than other sectors. We rely on similar arguments to show the importance of the role of international trade in adaptation to climate change. The recent quantitative trade literature uses the exact hat algebra (Dekle et al., 2007) to identify the minimum set of information necessary for obtaining counterfactual results. We show in this paper how to use this method to calibrate a spatially-explicit model on a limited set of spatial information, using the country-level aggregate information and the potential productivity of land to infer where crops are planted in the initial equilibrium.

The rest of this paper is organized as follows. Section 2 connects the dots between this paper and two related literatures: the one on acreage/land-use choice that deals with how landowners assign their land to particular uses and the one on international adaption to climate change in agriculture. Section 3 develops the general equilibrium model and makes clear, using the exact hat algebra, what information is needed for its calibration. Section 4 then describes the data used for calibration, distinguishing between the behavioral parameters that are selected from an extensive literature review and the baseline equilibrium values, which are constructed from various sources. The calibrated model is used in section 5 to simulate the counterfactual effects of climate change under the main calibration assumptions. In section 6, different calibrations are considered, varying the flexibility of every adjustment margins, which allows us to analyze the role of each margin and their influence on international trade. Section 7 offers some concluding remarks

2 Related literature

2.1 Acreage and land-use choice

One of the key theoretical problems in the representation of a landowner who allocates his land to its most profitable uses is to avoid corner solutions where all the land is allocated to one use or crop. Corner solutions are a challenge for applied modeling and are unrealistic when the focus is larger than one small field. In this paper, following CDS, the problem is dealt with by recognizing that the available data on potential yields at the field level (field being considered here generically as an extended area) represent only the expected yields for the whole field, but there is an unobserved within-field heterogeneity explaining that the specialization is not complete. Then, assuming that the within-field heterogeneity is described by a Type-II extreme value distribution delivers simple expressions of acreage choice.

While being inspired by the trade literature, our representation of crop choice shares many features with the approaches previously adopted in the agricultural economics and land-use literatures. One of them (e.g., Feng and Babcock, 2010; Lichtenberg, 1989; Stavins and Jaffe, 1990) emphasizes the heterogeneity of land and represents it in theoretical models of agricultural land use with probability distributions. A key distinction with our approach is in the choice of the probability distribution. With distributions other than an extreme value distribution (e.g., a lognormal in Stavins and Jaffe, 1990), it is necessary to order land uses by land quality so that their shares correspond to a compact support of the distribution, making cumbersome working with more than two crops (an approach similar to Dornbusch et al., 1977, Ricardian trade model). Using an extreme value distribution solves this problem and makes acreage and land-use choices easy to model.

Among the other justifications for a diversified crop portfolio are crop rotations (Hennessy, 2006) and risk diversification (Chavas and Holt, 1990). While both justifications are realities of agricultural production, these issues being inherently dynamic and stochastic, they could not be adequately represented in a static and deterministic model like the one under consideration. For the static analysis of crop choices, two main strategies have been pursued. First, multicrop models, built on duality theory (Chambers and Just, 1989), where the convexity of the cost function prevents full specialization on some crops (because of decreasing return to scale to specialize in one crop). This strategy yields very flexible representations that, however, tend to be difficult to interpret. Second, models where acreage or land-use shares are represented by systems of multinomial logit equations.[1] These multinomial logit models have two origins. They have emerged either as convenient reduced form approach for estimating allocation in shares (Wu and Segerson, 1995) or as outcomes from the maximization of random profit functions where the stochastic component follows a Type-I extreme value distribution (Chomitz and Gray, 1996). Multinomial logit models obtained from random profit maximization have mainly been used for analyzing land-use choices, but not for acreage choices.

[1] Carpentier and Letort (2013) have recently proposed a compromise between the flexible multicrop models and the multinomial logit models by developing a deterministic multicrop model yielding multinomial logit acreage shares.

So, using extreme value distributions is not new and has a long empirical tradition in the literature on land-use choices. However, there is one key difference in the approach pioneered by CDS and extended here with earlier work using extreme value distributions. The role of the stochastic specification is fundamentally different with earlier approaches. The stochastic term is not introduced for econometric purposes but has a clear theoretical interpretation which is to add within-field heterogeneity in yields to prevent complete specialization. The stochastic term eventually disappears from the equilibrium conditions of the model after being integrated. In addition, since the stochastic term enters multiplicatively and follows a Type-II extreme value distribution, it implies that the share equations do not strictly follow a logit form, but the implications of this difference is likely limited since an exponential transformation allows recovery of a logit.

One can also note that applied simulation models have faced the same issue of allocating the land factor to its various uses. However, in most applications, this was done without any connection to the acreage/land-use literature. For example, computable general equilibrium models usually follow the approach adopted in the GTAP model of allocating land with a Constant Elasticity of Transformation (CET) function. This choice leads to equations similar to those in this paper, with one big difference. A CET function, like its Constant Elasticity of Substitution (CES) counterpart, allocates shares in value but does not enforce equilibrium in volume in the sense that individual land uses do not add up to total available land. This limit makes this CET approach unsuitable for applications to environmental issues where a clear connection to physical land areas is necessary.

2.2 International trade and climate change

Questions of international trade and adaptation to climate change in agriculture started to be addressed in the early 1990s with partial equilibrium (Reilly and Hohmann, 1993) or general equilibrium models (Randhir and Hertel, 2000; Rosenzweig and Parry, 1994; Tsigas et al., 1997). While these studies often emphasized the role of international trade in justifying the use of models of the global economy, they do not specifically analyze the role of international trade in adaptation to climate change. Except for Randhir and Hertel (2000) who reach the counterintuitive conclusion that the adjustments facilitated by international trade could have detrimental welfare effects. This result arises in their paper because climate change leads to increase production in developed countries with high level of agricultural support; therefore, it aggravates preexisting distortions. While it is a valid and interesting point, empirically agricultural policies tend to evolve with comparative advantages and market conditions (Anderson et al., 2013) and, thus, are unlikely to stay the same with climate change. Consequently, in this model we prefer to abstain from representing agricultural policies, despite their prevalence.

These first works on international trade and adaptation to climate change all share the assumption that land is uniform within countries, neglecting the role that within-country heterogeneity of climate change effects may play in opening new adaptation possibilities. An additional difficulty is that when, land is uniform, defining the crop yields after climate change involves assuming a weighing scheme for the local yield changes. The weighing scheme adopted is usually based on current crop production, which negates the possibilities of more favorable yields under climate change elsewhere than where crops are currently produced.

The within-country heterogeneity of land, and its interaction with climate change, has recently received a lot of interests with papers using either gridded information or different land classes based on the agroecological zones framework (see, for example, Ahammad et al., 2015; Costinot et al., 2016; Leclère et al., 2014; Nelson et al., 2014; Wiebe et al., 2015). However, except for CDS, these more recent studies present the previously discussed limit of approaching land-use modeling with little connections with the theoretical and empirical land-use literature. And conversely, the land-use literature dealing with climate change tends to neglect market, and especially international trade, adaptations (Mendelsohn et al., 1994). A couple of papers using global models emphasize (Ahammad et al., 2015; Leclère et al., 2014) that trade patterns in agricultural products are likely to change a lot with climate change, without analyzing precisely what is the adaptive role of international trade. Only CDS do it and show that its role is likely limited.

3 Model

In this section, we develop a static general equilibrium model for analysis of global agricultural trade and land use. The model modifies and extends CDS' model by representing explicitly the elasticity of final demand for agricultural products, by considering almost all agricultural land uses without possibility of extension over other land uses, by representing livestock with the associated feed consumption, in particular pastures that account for a large part of land uses, and by adding trade resistances for the outside good.

3.1 Model setup

Consider a world economy composed of multiple regions indexed by $i \in \mathcal{I}$. Goods are indexed by $k \in \mathcal{K}$, where the non-agricultural bundle is indexed by $k = 0$. Agricultural goods include crops gathered in the set $\mathcal{K}^c \subset \mathcal{K}$ and one sector of livestock products indexed by $k = \text{l}$. Crops are defined here extensively as anything that requires land to grow. The production of livestock requires land only indirectly through its demand of crops for feed. One crop, we call grass and index by $k = \text{g}$, is not internationally tradable, because it represents forage crops that are directly grazed by animals and fodder crops (e.g., alfalfa hay) that have a too low value-to-weight ratio to be tradable. Grass is only used to feed livestock. Agricultural goods that are internationally traded (crops and livestock) and object of final consumption are gathered in the set $\mathcal{K}^a \subset \mathcal{K}$. Each region is endowed with two factors of production, labor and land, land being only used to grow crops. Land in region 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 $\omega \in [0, 1]$.

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

$$U_i = C_i^0 + \beta_i^{1/\epsilon} \begin{cases} C_i^{1-1/\epsilon}/(1-1/\epsilon) & \text{if } \epsilon \neq 1, \\ \ln C_i & \text{if } \epsilon = 1, \end{cases} \tag{1}$$

where $\epsilon > 0$ is the opposite of the price elasticity of demand for the agricultural bundle and $\beta_i > 0$ parameterizes the demand for the agricultural bundle. With these preferences, the consumption of the agricultural good is inelastic to income. This is consistent with the situation in developed countries because the income elasticity of the demand for primary products for food consumption converges to zero with income per capita (Gouel and Guimbard, forthcoming). In poor countries, however, the income elasticity of food consumption can be expected from Engel's law to be positive but inferior to one. It means that in very poor countries, where the income elasticity of food is the highest, the assumption of quasi-linear preferences underestimates the reduction in food consumption caused by climate change.

The bundle of agricultural goods is a CES composite:

$$C_i = \left[\sum_{k \in \mathcal{K}^a} \left(\beta_i^k\right)^{1/\kappa} \left(C_i^k\right)^{(\kappa-1)/\kappa} \right]^{\kappa/(\kappa-1)}, \tag{2}$$

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

Following the Armington assumption, the final consumption of each good, including the non-agricultural good, is itself a CES function of the consumption of varieties from different origins:

$$C_i^k = \left[\sum_{j \in \mathcal{I}} \left(\beta_{ji}^k\right)^{1/\sigma^k} \left(C_{ji}^k\right)^{(\sigma^k-1)/\sigma^k} \right]^{\sigma^k/(\sigma^k-1)}, \tag{3}$$

where $\sigma^k > 0$ is the elasticity of substitution between varieties from different regions, C_{ji}^k is the export for final consumption from region j to region i of good k, and $\beta_{ji}^k \geq 0$ is an exogenous preference parameter. The outside good is concerned by this modeling because through the preference parameters β_{ji}^0 and the finite elasticity of substitution it will introduce multilateral resistances to trade (Anderson and van Wincoop, 2003).[2] These resistances may be important for the analysis of the trade effects of climate change because if a country is forced to import more agricultural goods because of climate change, it will have to pay for these imports by exporting more the outside good. This change of specialization necessarily involves frictions as other countries may not accept these additional exports without reductions in prices. The multilateral resistances will serve as proxies for these frictions and will generate terms-of-trade effects associated with the changes in export prices.

Technology

Non-agricultural good The non-agricultural good is produced with labor only and constant return to scale:

$$Q_i^0 = N_i^0 / \nu_i^0, \tag{4}$$

where Q_i^0 is the quantity produced, N_i^0 is the corresponding labor demand, and $\nu_i^0 > 0$ is a shifter of productivity.

Crops Crops are produced by combining land and labor. Land and labor are complementary, so, on every parcel ω, if the crop $k \in \mathcal{K}^c$ is planted the production per unit of land is given by

$$Q_i^{fk}(\omega) = \min\left(A_i^{fk}(\omega), N_i^{fk}(\omega) / \nu_i^k\right), \tag{5}$$

where $A_i^{fk}(\omega) \geq 0$ is the productivity of land (the yield), $N_i^{fk}(\omega)$ is the quantity of labor used in production, and ν_i^k is the unit labor requirement per unit of land. Following CDS, we assume that yields are 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} is the unconditional average yield of the field, $A_i^{fk} = \mathrm{E}[A_i^{fk}(\omega)]$, and $\Gamma(\cdot)$ is the Gamma function.[3] θ characterizes the heterogeneity within fields, with a higher θ indicating more homogeneity.

We 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 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 small growing seasons or elevated slopes. However, this assumption neglects the fact that pastures and hay fields are actively managed and are not simply rangelands. This problem goes beyond this model. 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.

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. This choice implies that we neglect any extensive margin of land use. In the model, one cannot extend, or reduce, agricultural land use over forests, protected areas, or urban areas. Indeed, such choices are inherently dynamic – for example, foregoing annual benefits from crop production to receive future benefits from timber exploitation – they involve switching costs, and they strongly depend on local institutions and legal enforcement as deforestation is often illegal. These decisions would be challenging to model and to estimate at a global scale (Scott, 2014) and so are neglected here. This choice could create a possible bias by not representing one

[2] An Eaton and Kortum (2002) specification could equivalently have been adopted for the outside good.

[3] The cumulative distribution function of a Fréchet distribution with shape parameter θ and scale parameter s is given by $\Pr(X \leq x) = \exp\left(-(x/s)^{-\theta}\right)$ if $x > 0$.

margin of adaptation to climate change. But this margin of adjustment creates other problems because it involves an adaptation strategy going against the mitigation of greenhouse gas emissions. Indeed, forest are important stocks of carbon that would be released in the atmosphere upon clearing. So, rather than a biased estimate, one can see the results here as a counterfactual where adaptation is done without deforestation (Erb et al., 2016).

Since here the only choice of a landowner is which crop to grow on a parcel, this model neglects the possibility of changes in land management, for example by investing in irrigation, adopting new seeds, switching to double cropping, or increasing the use of fertilizers. With very heterogeneous estimation results, the size of the elasticity of yield to producer price is a contentious issue in agricultural economics that was at the heart of the recent debate on the indirect land use change effects of biofuels policies (Keeney and Hertel, 2009). In addition to their variability, available estimates concern only a small subset of the planted crops. So, we adopt the pessimistic side of the literature by assuming no yield response. However, we assess the sensitivity of the results to this crucial assumption.

Livestock Livestock products are produced by combining feed and labor:

$$Q_i^{\mathrm{l}} = \min\left(\frac{x_i}{\mu_i}, \frac{N_i^{\mathrm{l}}}{\nu_i^{\mathrm{l}}}\right), \tag{6}$$

where x_i is the demand for feed and the parameter μ_i is known in zootechnics as the feed conversion ratio: the quantity of feeds necessary to produce one unit of animal output.

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, we assume that the feed mix technology takes a CES form:

$$x_i = \left[\sum_{k\in\mathcal{K}^c} \left(\beta_i^{k,\mathrm{feed}}\right)^{1/\varsigma} \left(x_i^k\right)^{(\varsigma-1)/\varsigma}\right]^{\varsigma/(\varsigma-1)}, \tag{7}$$

where $\varsigma > 0$ 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 sake of parsimony, 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 (3).

Market structure and trade costs All markets are perfectly competitive. Despite the land heterogeneity between fields, we neglect domestic trade costs and assume that 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 greatly simplifies the modeling of livestock by avoiding the need to represent livestock production by field.

International trade entails trade costs. We consider iceberg trade costs. $\tau_{ij}^k \geq 1$ units must be shipped from country i to country j in order to sell a variety of sector k. The absence of arbitrage opportunities implies that

$$p_{ij}^k = \tau_{ij}^k p_i^k, \tag{8}$$

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.

With in average higher level of protection than in other sectors, agricultural products support a disproportionate share of trade and domestic policies in the world. We do not represent them here because maintaining these policies constant with the new pattern of comparative advantages caused by climate change would make little sense.

3.2 Equilibrium in levels

Good demand Given the households quasi-linear preferences in equation (1), utility maximization implies the following demand for the bundle of agricultural products:

$$C_i = \begin{cases} \beta_i \left(P_i/P_i^0\right)^{-\epsilon} & \text{if } E_i \geq \beta_i P_i^{1-\epsilon}\left(P_i^0\right)^{\epsilon}, \\ E_i/P_i & \text{if } E_i < \beta_i P_i^{1-\epsilon}\left(P_i^0\right)^{\epsilon}, \end{cases} \tag{9}$$

where E_i is the country expenditures and P_i is the price of the bundle of agricultural goods given by

$$P_i = \left[\sum_{k\in\mathcal{K}^a} \beta_i^k \left(P_i^k\right)^{1-\kappa}\right]^{1/(1-\kappa)}, \tag{10}$$

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

From equation (2), the demand of the bundle of product $k \in \mathcal{K}^a$ is given by

$$C_i^k = \beta_i^k \left(\frac{P_i^k}{P_i}\right)^{-\kappa} C_i. \tag{11}$$

The demand for the outside good is given by the household's budget constraint:

$$P_i^0 C_i^0 = E_i - P_i C_i. \tag{12}$$

It can possibly be equal to 0 if $E_i < \beta_i P_i^{1-\epsilon}\left(P_i^0\right)^{\epsilon}$.

Production Cost minimization in the non-agricultural sector implies from equation (4) that the price of the outside good varies proportionally to wages, w_i:

$$p_i^0 = \nu_i^0 w_i. \tag{13}$$

From equations (6) and (7), cost minimization in the livestock feed sector implies for $k \in \mathcal{K}^c$:

$$x_i = \mu_i Q_i^{\mathrm{l}}, \tag{14}$$

$$N_i^{\mathrm{l}} = \nu_i^{\mathrm{l}} Q_i^{\mathrm{l}}, \tag{15}$$

$$p_i^{\mathrm{l}} = \nu_i^{\mathrm{l}} w_i + \mu_i P_i^{\mathrm{feed}}, \tag{16}$$

$$x_i^k = \beta_i^{k,\mathrm{feed}} \left(\frac{P_i^k}{P_i^{\mathrm{feed}}}\right)^{-\varsigma} x_i = \beta_i^{k,\mathrm{feed}} \left(\frac{P_i^k}{P_i^{\mathrm{feed}}}\right)^{-\varsigma} \mu_i Q_i^{\mathrm{l}}, \tag{17}$$

$$P_i^{\mathrm{feed}} = \left[\sum_{k\in\mathcal{K}^c} \beta_i^{k,\mathrm{feed}} \left(P_i^k\right)^{1-\varsigma}\right]^{1/(1-\varsigma)}, \tag{18}$$

where P_i^{feed} is the price index corresponding to the demand for the feed bundle x_i.

The Leontief structure of crop production in equation (5) implies on parcel ω the following factor demands per unit of land if the parcel is planted with $k \in \mathcal{K}^c$:

$$Q_i^{fk}(\omega) = A_i^{fk}(\omega) = N_i^{fk}(\omega)/\nu_i^k. \tag{19}$$

The difference between the revenue from crop production and the labor cost is the land rent. The rent accruing to the parcel of land ω when used to grow k is

$$p_i^k Q_i^{fk}(\omega) - w_i N_i^{fk}(\omega) = \left(p_i^k - w_i \nu_i^k\right) A_i^{fk}(\omega), \tag{20}$$

which is distributed according to a Fréchet with parameters θ and $\gamma r_i^k A_i^{fk}$ if $r_i^k > 0$ and where

$$r_i^k \equiv p_i^k - w_i \nu_i^k \tag{21}$$

is the land rent per unit of production at the country level.

To maximize its profit the landowner plants a parcel with the crop delivering the highest land rents, $r_i^k A_i^{fk}(\omega)$. 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

$$\pi_i^{fk} = \frac{\left(r_i^k A_i^{fk}\right)^\theta}{\sum_{l \in \mathcal{K}^c, r_i^l \geq 0} \left(r_i^l A_i^{fl}\right)^\theta}. \tag{22}$$

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.

Total output of crop k by field f is given by the product of the surface of the field, the share of acreage devoted to crop k, and the average yields conditional on the crop having been chosen for production:

$$Q_i^{fk} = s_i^f \pi_i^{fk} \operatorname{E}\left[A_i^{fk}(\omega) \,|\, r_i^k A_i^{fk}(\omega) \in \arg\max_{l \in \mathcal{K}^c} r_i^l A_i^{fl}(\omega)\right]. \tag{23}$$

From the standard properties of the Fréchet distribution we have

$$E\left[r_i^k A_i^{fk}(\omega) \,|\, r_i^k A_i^{fk}(\omega) \in \arg\max_{l \in \mathcal{K}^c} r_i^l A_i^{fl}(\omega)\right] = \left[\sum_{l \in \mathcal{K}^c, r_i^l \geq 0} \left(r_i^l A_i^{fl}\right)^\theta\right]^{1/\theta}, \tag{24}$$

so

$$Q_i^{fk} = s_i^f A_i^{fk} \left(\pi_i^{fk}\right)^{(\theta-1)/\theta}, \tag{25}$$

and country-level production is

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

Similarly, the total land rents from growing crop k are

$$R_i^k = \sum_{f \in \mathcal{F}_i} s_i^f \pi_i^{fk} E\left[r_i^k A_i^{fk}(\omega) \,|\, r_i^k A_i^{fk}(\omega) \in \arg\max_{l \in \mathcal{K}^c} r_i^l A_i^{fl}(\omega)\right] = r_i^k Q_i^k. \tag{27}$$

The labor demand corresponding to crop production is simply determined from the technical requirements:

$$N_i^k = \nu_i^k Q_i^k. \tag{28}$$

Based on the previous equations, one can calculate the own-price supply elasticity for crops which is given by

$$\frac{\partial \ln Q_i^k}{\partial \ln p_i^k} = (\theta - 1) \frac{p_i^k}{r_i^k} \sum_{f \in \mathcal{F}_i} \left(1 - \pi_i^{fk}\right) \frac{Q_i^{fk}}{Q_i^k}. \tag{29}$$

θ appears as the parameter governing supply elasticity. A higher θ, which corresponds to more homogeneous fields, implies also a more elastic supply. The second term, the ratio of producer price to land rent p_i^k/r_i^k, allows to convert the supply elasticity with respect to land rents into the own-price elasticity. It is greater than 1 as it equals 1 plus the ratio of unit labor costs to land rents. The last term, $\sum_{f \in \mathcal{F}_i}(1 - \pi_i^{fk})Q_i^{fk}/Q_i^k$, shows that the elasticity is non-constant and depends on the acreage. For a crop with very small acreage, $\pi_i^{fk} \approx 0$, the elasticity is $(\theta - 1)\, p_i^k/r_i^k$. The elasticity decreases when acreages increase to reach eventually 0 when $\pi_i^{fk} \approx 1$.

International trade Preferences over the countries of origin have been assumed similar for final consumption and for livestock feed, so based on equation (3) the index price that aggregates the price of varieties from various origins is

$$P_i^k = \left[\sum_{j \in \mathcal{I}} \beta_{ji}^k \left(\tau_{ji}^k p_j^k\right)^{1-\sigma_k}\right]^{1/(1-\sigma_k)}, \tag{30}$$

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

$$X_i^k/P_i^k = C_i^k + \mathbf{1}_{k \in \mathcal{K}^c} \left(x_i^k\right) \tag{31}$$

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

$$X_{ji}^k = \beta_{ji}^k \left(\frac{\tau_{ji}^k p_j^k}{P_i^k}\right)^{1-\sigma_k} X_i^k. \tag{32}$$

Market clearing conditions The market equilibrium for goods is given by the equality between the value of production and export demand from all countries, for $k \in \mathcal{K}$:

$$p_i^k Q_i^k = \sum_{j \in \mathcal{I}} X_{ij}^k. \tag{33}$$

The equation of labor market clearing states that labor endowment, N_i, is equal to labor demand from all sectors:

$$N_i = \sum_{k \in \mathcal{K}} N_i^k = \sum_{k \in \mathcal{K}} \nu_i^k Q_i^k. \tag{34}$$

Budget constraint Final expenditure in country i is the sum of labor income, land rents, and trade deficits denoted Δ_i:

$$E_i = w_i N_i + \sum_{k \in \mathcal{K}^c} R_i^k + \Delta_i. \tag{35}$$

From the above we can define the competitive equilibrium as follows

Definition. A competitive equilibrium 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 goods (C_i^k), production (Q_i^k), feed demand (x_i^k), aggregate feed price (P_i^{feed}), land rent per unit of production (r_i^k), acreage share (π_i^{fk}), land rent (R_i^k), consumption price (P_i^k), total imports (X_i^k), bilateral exports (X_{ij}^k), producer price (p_i^k), wage (w_i), and expenditures (E_i) such that equations (9)–(13), (16)–(18), (21), (22), (26), (27), and (30)–(35) hold.

3.3 Equilibrium in relative changes

To make explicit what are the data necessary to calibrate this model, we adopt the exact hat algebra / calibrated share form (Dekle et al., 2007; Rutherford, 2002) and express the model in relative changes with $\hat{v} \equiv v'/v$ the relative changes of any variable v between the baseline and the counterfactual equilibria. We consider two sources of exogenous shocks: changes in trade deficits and changes in crop productivity.

The model presents two situations where regime changes could occur, which should prevent expressing the equations in relative changes. First, with a quasi-linear utility, the consumption of the outside good can reach zero if income is not high enough compared to relative prices. This is an exceptional situation, possible only for extreme calibration/shocks, so we neglect its possibility and verify after the simulations that we are still in the interior solution. Second, the production of crop k is undertaken in country i only if the land rent per unit of production, r_i^k, is positive. Because of the Armington assumption, we should not expect any regime change after counterfactual shocks to crop productivity. Even after an increase in potential yields, a crop that is not initially produced will not be planted, because it would find no local or foreign demand (preference parameters, β_{ji}^k, are initialized to 0 without initial production in j). Similarly, if potential yields are not zero in all fields, an initially positive production cannot be stopped by a decrease in potential yield since this country crop is considered imperfectly substitutable to the same crop from other countries. So, we can safely ignore the possibility of regime changes and express the model in relative changes.

To express the equations in relative changes, we introduce share parameters. $\alpha_i^k = P_i^k C_i^k / P_i C_i$ is the budget share of product k in the consumption of all agricultural good. $\alpha_i^{k,\text{feed}} = P_i^k x_i^k / P_i^{\text{feed}} x_i$ is budget share of crop k in livestock feed. $\alpha_{ji}^k = X_{ji}^k / X_i^k$ is the bilateral trade share. Finally, we introduce $\phi_i^{k,\text{labor}}$, $\phi_i^{k,\text{land}}$, and $\phi_i^{k,\text{feed}}$ the budget shares of each input of production: labor, land, and feed. They allow to express the zero-profit condition in the same way for all sectors as

$$\hat{p}_i^k = \phi_i^{k,\text{labor}} \hat{w}_i + \phi_i^{k,\text{land}} \hat{r}_i^k + \phi_i^{k,\text{feed}} \hat{P}_i^{\text{feed}}. \tag{36}$$

To allow for the possibility that fields may have zero potential yields in some crops in the baseline, but positive ones under climate change, we express changes in crop productivity in levels and not in relative changes. Consequently, after substitution of the acreage share, the equation associated with crop production is

$$\hat{Q}_i^k = \sum_{f \in \mathcal{F}_i} \frac{s_i^f A_i^{fk\prime}}{Q_i^k} \frac{\left(r_i^k \hat{r}_i^k A_i^{fk\prime}\right)^{\theta-1}}{\left[\sum_{l \in \mathcal{K}^c} \left(r_i^l \hat{r}_i^l A_i^{fl\prime}\right)^{\theta}\right]^{(\theta-1)/\theta}} \text{ for all } k \in \mathcal{K}^c. \tag{37}$$

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

$$\hat{C}_i = \left(\hat{P}_i / \hat{P}_i^0\right)^{-\epsilon}, \tag{38}$$

$$\hat{P}_i = \left[\sum_{k \in \mathcal{K}^a} \alpha_i^k \left(\hat{P}_i^k\right)^{1-\kappa}\right]^{1/(1-\kappa)}, \tag{39}$$

$$\hat{C}_i^k = \left(\hat{P}_i^k / \hat{P}_i\right)^{-\kappa} \hat{C}_i \text{ for all } k \in \mathcal{K}^a, \tag{40}$$

$$P_i^0 C_i^0 \hat{P}_i^0 \hat{C}_i^0 = E_i \hat{E}_i - P_i C_i \hat{P}_i \hat{C}_i, \tag{41}$$

$$\hat{x}_i^k = \left(\hat{P}_i^k / \hat{P}_i^{\text{feed}}\right)^{-\varsigma} \hat{Q}_i^l \text{ for all } k \in \mathcal{K}^c, \tag{42}$$

$$\hat{P}_i^{\text{feed}} = \left[\sum_{k\in\mathcal{K}^c} \alpha_i^{k,\text{feed}} \left(\hat{P}_i^k\right)^{1-\varsigma}\right]^{1(1-\varsigma)}, \tag{43}$$

$$\hat{P}_i^k = \left[\sum_{j\in\mathcal{I}} \alpha_{ji}^k \left(\hat{p}_j^k\right)^{1-\sigma_k}\right]^{1/(1-\sigma_k)}, \tag{44}$$

$$X_i^k \hat{X}_i^k = P_i^k C_i^k \hat{P}_i^k \hat{C}_i^k + \mathbf{1}_{k\in\mathcal{K}^c}\left(P_i^k x_i^k \hat{P}_i^k \hat{x}_i^k\right), \tag{45}$$

$$\hat{X}_{ji}^k = \left(\hat{p}_j^k / \hat{P}_i^k\right)^{1-\sigma_k} \hat{X}_i^k, \tag{46}$$

$$p_i^k Q_i^k \hat{p}_i^k \hat{Q}_i^k = \sum_{j\in\mathcal{I}} X_{ij}^k \hat{X}_{ij}^k, \tag{47}$$

$$w_i N_i = \sum_{k\in\mathcal{K}} w_i N_i^k \hat{Q}_i^k, \tag{48}$$

$$E_i \hat{E}_i = w_i N_i \hat{w}_i + \sum_{k\in\mathcal{K}^c} R_i^k \hat{r}_i^k \hat{Q}_i^k + \Delta_i \hat{\Delta}_i. \tag{49}$$

These equations make clear the information needed for calibrating the model. As for any general equilibrium model, we need aggregate information in value at the country or sector level such as final expenditures, trade flows, production values, or the various budget shares previously mentioned. We will take these values from the FAOSTAT and GTAP datasets. We need field-level information about potential yields that will come from the GAEZ project. Finally, in equation (37), appear the land rent per unit of production, r_i^k, and the volume of crop production, Q_i^k. We show now that given field-level potential yields, A_i^{fk}, and aggregate moments we can recover uniquely these initial values.

We can note that using equations (22), (26), and (27), we have

$$\left(r_i^k\right)^{-\theta} = \left(R_i^k\right)^{-1} \sum_{f\in\mathcal{F}_i} s_i^f \left(A_i^{fk}\right)^{\theta} \left[\sum_{l\in\mathcal{K}_c} \left(r_i^l A_i^{fl}\right)^{\theta}\right]^{(1-\theta)/\theta}. \tag{50}$$

Using the contraction mapping theorem, we show in appendix A that this equation has a unique solution. So, for each country, given positive values for R_i^k, s_i^f, and A_i^{fk}, from any set of initial positive land rents, $\{r_i^k > 0 | k \in \mathcal{K}^c, R_i^k > 0\}$, one can do a fixed-point iteration between the right-hand side and the left-hand side, which will converge to the equilibrium value of land rents. From the equilibrium values of r_i^k, we can calculate the acreage shares, π_i^{fk}, from equation (22) and the initial production levels, Q_i^k, from equation (26).

The model results would be similar if a country-crop productivity shifter was used to adjust the potential yields A_i^{fk} (see proof in appendix B). This is an important result because the potential yields calibrated on the GAEZ data can be very different from the realized yields. They can differ, for example, because of yield gaps, multiple cropping, or technological changes with respect to the time-period of data underlying the crop model calibration. The invariance to the presence of productivity shifters implies that the model is robust to these measurement errors in the potential yields. It means also that the model does not need to account for the economic and institutional reasons that may explain the low levels of yields in low-income countries. Consequently, what matters for calibrating field-level information is the difference between fields for a given country-crop couple.

Equations (36)–(49) represent a square system of nonlinear equations and can be solved with any solver for systems of nonlinear equations. In this paper, the model is solved using the solvers available under GAMS.

3.4 Welfare

Welfare changes from climate change are evaluated by calculating the equivalent variation.[4] For an interior solution, the household expenditure function is

$$e\left(P_i^0, P_i, U_i\right) = P_i^0 U_i + \beta_i \left(P_i^0\right)^{\epsilon} \begin{cases} P_i^{1-\epsilon}/(1-\epsilon) & \text{if } \epsilon \neq 1, \\ \left[1 - \ln\left(\beta_i P_i^0/P_i\right)\right] & \text{if } \epsilon = 1, \end{cases} \tag{51}$$

and for a corner solution (i.e., if the consumption of the outside good is at its zero lower bound), it is (see appendix C.1 for the calculation of the welfare expressions in the case of a corner solution)

$$e\left(P_i^0, P_i, U_i\right) = P_i \begin{cases} \beta_i^{1/(1-\epsilon)} \left[(1-1/\epsilon) U_i\right]^{1/(1-1/\epsilon)} & \text{if } \epsilon \neq 1 \text{ and } U_i < \left[\beta_i/(1-1/\epsilon)\right] \left(P_i/P_i^0\right)^{1-\epsilon}, \\ \exp\left(U_i/\beta_i\right) & \text{if } \epsilon = 1 \text{ and } U_i < \beta_i \ln\left(\beta_i P_i^0/P_i\right). \end{cases} \tag{52}$$

In the model, corner solutions can only occur for unlikely combinations of behavioral parameters that lead to extreme price variations under climate change and so have been neglected when defining the model in relative changes, but they cannot be neglected for the calculation of the equivalent variation. Calculating the equivalent variation involves combining the counterfactual utility with initial prices. If utility decreases a lot, this combination could correspond to a corner solution. The equivalent variation for an interior solution and expressed in terms of variables in relative changes is

$$EV_i = e\left(P_i^0, P_i, U_i'\right) - e\left(P_i^0, P_i, U_i\right) = P_i^0 C_i^0 \left(\hat{C}_i^0 - 1\right) + P_i C_i \begin{cases} \left(\hat{C}_i^{1-1/\epsilon} - 1\right)/(1-1/\epsilon) & \text{if } \epsilon \neq 1, \\ \ln \hat{C}_i & \text{if } \epsilon = 1. \end{cases} \tag{53}$$

For a corner solution, it is

$$EV_i = \begin{cases} \left(P_i C_i\right)^{1/(1-\epsilon)} \left[(1-1/\epsilon) P_i^0 C_i^0 \hat{C}_i^0 + P_i C_i \hat{C}_i^{1-1/\epsilon}\right]^{1/(1-1/\epsilon)} - E_i & \text{if } \epsilon \neq 1, \\ P_i C_i \hat{C}_i \exp\left[\left(P_i^0 C_i^0/P_i C_i\right) \hat{C}_i^0\right] - E_i & \text{if } \epsilon = 1. \end{cases} \tag{54}$$

A corner solution occurs only if

$$\begin{cases} (1-1/\epsilon)\left(P_i^0 C_i^0/P_i C_i\right) \hat{C}_i^0 + \hat{C}_i^{1-1/\epsilon} < 1 & \text{if } \epsilon \neq 1, \\ P_i^0 C_i^0 \hat{C}_i^0 + P_i C_i \ln \hat{C}_i < 0 & \text{if } \epsilon = 1. \end{cases} \tag{55}$$

To help interpret the welfare results, we approximate the equivalent variation at the first order (see appendix C.2). Neglecting changes in trade deficits that will be removed before simulating the effects of climate change, it gives the following decomposition:

$$\mathrm{d}\, EV_i = \underbrace{\sum_{k \in \mathcal{K}, j \in \mathcal{I}} \left(X_{ij}^k \,\mathrm{d}\ln p_i^k - X_{ji}^k \,\mathrm{d}\ln p_j^k\right)}_{\text{Terms-of-trade effects}} + \underbrace{\sum_{f \in \mathcal{F}_i, k \in \mathcal{K}^c} r_i^k Q_i^{fk} \,\mathrm{d}\ln A_i^{fk}}_{\text{Productivity effects}}. \tag{56}$$

In the absence of any distortion in the model, this decomposition is very simple with two terms. The first is the welfare effect of changes in terms of trade. They sum to zero at the world level. The second is the welfare effect of changes in crop yields at the initial acreage choices and prices.

This decomposition approximates well the welfare changes for an interior solution and for small changes. The

[4]In this setting where the price of the outside good is not constant and varies with domestic wage, even if the representative household has quasi-linear utility, the consumer surplus would be different from equivalent variation.

changes in yield from climate change are large, on average −13.2%, and values such as −50% or +50% are not unusual, so these are not marginal changes that would make valid the first-order approximation in equation (56). With these large changes, the first-order approximation is very imprecise. To obtain a precise decomposition of the welfare changes, we follow Harrison et al.'s (2000) method and integrate the welfare decomposition along a line:

$$EV_i = \sum_{k\in\mathcal{K},j\in\mathcal{I}} \int_{t=0}^{1} \left(X_{ij}^{k}(t) \frac{\mathrm{d}\ln p_i^k}{\mathrm{d}t} - X_{ji}^{k}(t) \frac{\mathrm{d}\ln p_j^k}{\mathrm{d}t} \right) \mathrm{d}t + \int_{t=0}^{1} \sum_{f\in\mathcal{F}_i,k\in\mathcal{K}^c} r_i^k(t)\, Q_i^{fk}(t) \frac{\mathrm{d}\ln A_i^{fk}}{\mathrm{d}t}\,\mathrm{d}t, \tag{57}$$

where t parameterizes the yield changes. The resulting decomposition is known to be path-dependent, as terms-of-trade and productivity effects could react differently depending on which countries or crops are affected first. Without any information on the timing of yield changes, we simply divide yields regularly between their initial and final values: $tA_i^{fk\prime} + (1-t)A_i^{fk}$. We will complement the interpretation of this decomposition with other results going in the same directions, mitigating concerns about the path-dependency.

4 Taking the model to the data

When calibrating the model, it is important for several reasons to represent most agricultural commodities. First, if almost all the sources of calories are included in the model, then $-\epsilon$ can be interpreted as the price elasticity of food demand for which there is an abundant literature (e.g., Gao, 2012; Subramanian and Deaton, 1996). With a small subset of agricultural commodities, this elasticity would be more difficult to interpret as it would be a composite of the price elasticity of food demand and of the elasticity of substitution between crops in the model and the non-represented crops. Secondly, some crops may make a minor contribution to global crop production but be of crucial importance in some countries. For example, roots and tubers such as cassava, sweet potatoes, or yams are staple foods in many African countries even if they represent a small share of global crop production and trade, especially trade. Lastly, climate change will affect all crops differentially. So, neglecting some crops with non-negligible land use implies not taking into account the opportunity cost of reallocating production on the land they were previously grown.

The model is calibrated on 35 crops and 50 countries/regions with a 2011 base year for the data. Table 2 lists the countries and crops included in the sample and indicates their respective share of world agricultural area and world output in value. For computational reasons, all countries are not included separately, but countries that are not are aggregated in 9 regions based on their geographical location (mapping between regions and countries available in table A1). The countries represented separately have been chosen based on their share of world output in crops and their share of world agricultural area, but also chosen to illustrate a diversity of exposures to climate change. All crops from the GAEZ project with a mapping with FAOSTAT crops have been included in the model, but some have been aggregated. Excluding grass, the crops represented in the model correspond to 88% of the 2011 global harvested areas in FAOSTAT and therefore to a even higher share of agricultural land uses when pastures are accounted for.

4.1 Behavioral parameters

Price elasticity of agricultural good demand Given that the model includes almost all agricultural products and that these products are mostly consumed as food with the exception of fibers (cotton and flax) and tobacco, then it proceeds that the elasticity ϵ can be approximated as a food demand elasticity. We have identified two sets of literature related to food demand elasticities relevant to this study. The first is the literature on the elasticity of the calorie consumption with respect to total expenditure, in which papers occasionally also report elasticities of calorie price. Studying demand for calories in six developing countries, Knudsen and Scandizzo (1982, Table 3) show that the elasticity of calorie price decreases in absolute value with income. In the lowest quartiles, the elasticities are between −0.88 and −0.45 depending on the countries, while in the highest quartiles they are between −0.11 and −0.07. Based on a survey of rural Indian households, Subramanian and Deaton (1996, Figure 5) find elasticities between −0.4 and −0.3, also decreasing

Table 2: List of sample countries and crops

Country	Share of world area (%)[a]	Share of world output (%)[b]	Country	Share of world area (%)[a]	Share of world output (%)[b]
Argentina	3.27	1.21	Pakistan	0.73	1.37
Australia	6.87	1.33	Peru	0.53	0.44
Bangladesh	0.22	0.46	Philippines	0.24	0.83
Brazil	5.71	5.10	Poland	0.40	0.79
Canada	1.10	1.47	Romania	0.32	0.50
China (including Hong Kong)	9.97	21.18	Russia	3.90	2.42
Colombia	0.88	0.65	Senegal	0.20	0.05
Egypt	0.10	0.60	South Africa	2.11	0.55
Ethiopia	0.88	0.37	Spain	0.59	1.58
France	0.74	2.44	Sri Lanka	0.06	0.10
Germany	0.42	2.20	Thailand	0.40	0.89
Greece	0.10	0.45	Turkey	0.87	1.47
India	4.39	8.18	Ukraine	1.03	0.74
Indonesia	1.55	2.94	United Kingdom	0.39	1.15
Iran	1.32	0.94	United States	8.58	11.09
Italy	0.25	1.71	Viet Nam	0.23	0.68
Japan	0.10	2.53	Caribbean	0.31	0.49
Kazakhstan	5.06	0.47	Central America	0.57	0.61
Kenya	0.68	0.21	Rest of Asia	3.57	1.67
Korea, South	0.03	0.79	Rest of Commonwealth of Independent States	2.13	1.06
Malaysia	0.19	0.68	Rest of Europe	1.40	4.04
Mexico	2.37	1.32	Rest of Middle East and North Africa	2.45	2.21
Morocco	0.57	0.35	Rest of Oceania	0.28	0.60
Netherlands	0.05	0.82	Rest of South America	2.91	1.48
Nigeria	1.48	1.30	Rest of Sub-Saharan Africa	17.48	3.49
Crop			**Crop**		
Banana		1.58	Olive		0.59
Barley		0.83	Onion		0.91
Beans		0.61	Other pulses		0.46
Buckwheat		0.03	Peas		0.11
Cabbage		0.53	Rapeseed		0.97
Carrot		0.35	Rice		8.86
Citrus fruits		1.70	Rye		0.08
Cocoa		0.23	Sorghum		0.43
Coconut		0.31	Soybean		3.20
Coffee		0.58	Sugar crops		3.08
Cotton		2.51	Sunflower		0.52
Flax		0.03	Tea		0.34
Grass		47.75	Tobacco		0.52
Groundnut		0.92	Tomato		2.47
Maize		6.55	Tropical roots and tubers		3.24
Millet		0.27	Wheat		5.05
Oat		0.12	White potato		2.93
Oil palm		1.35			

Sources: [a] Extension to 2007 of Ramankutty and Foley (1999). [b] Model values for the initial equilibrium based on FAOSTAT and GTAP as described in section 4.2.

with income. However, this literature does not provide aggregate elasticities at the country level. The second relevant literature does it since it is concerned with country-level estimate of final demand for food. Seale and Regmi (2006) and Gao (2012) estimate at the country level on ICP data, respectively, a complete demand system and a reduced-form food demand. As well as for the estimates on household surveys, they confirm the intuition that the price elasticity decreases in absolute value with income. Seale and Regmi (2006, Table 4) reports uncompensated elasticities going from −0.76 for Vietnam to −0.09 for the United States. Gao's (2012, Table A1) elasticities are similar: from −0.76 for the Democratic Republic of Congo to −0.16 for the United States.

Final food demand elasticities tend to be higher in absolute value than calorie elasticities. Gao's food demand elasticities for Bangladesh, India, and Morocco are −0.7, −0.66, and −0.63. They are close to Knudsen and Scandizzo's calorie elasticities for the lowest quartiles, 30 years before, and for India higher than Subramanian and Deaton's calorie elasticities for rural households. Aside from the different periods, a likely reason for higher values for final food demand elasticities is that they concerned processed food products, and while it is natural that households try to protect their caloric intake from adverse price shocks they have more flexibility to adjust the level of processing in their food demand. The elasticity ϵ in the model is likely to be closer to a calorie elasticity than to a final food demand elasticity since the model represents the demand for unprocessed agricultural products. It is not exactly a calorie elasticity because the CES nest below the quasi-linear utility function precludes a perfect representation as calories.

Following these considerations, we adopt $\epsilon = 0.2$. This parameter will play a crucial role in the results, because it will determine whether adaptation to climate change occurs through a reduction in demand for agricultural products or through higher prices which would trigger other margins of adjustment. Its role will be assessed in section 6, facilitated by the fact that the literature gives us clear lower and upper bounds.

Elasticity of substitution between agricultural products for final demand To choose the elasticity of substitution between agricultural products for final demand, one should first note that it determines the price elasticity of final demand for agricultural goods, jointly with the price elasticity of demand for the agricultural bundle and the budget shares. From equations (38)–(40), this elasticity is

$$\frac{\partial \ln C_i^k}{\partial \ln P_i^k} = -\kappa + (\kappa - \epsilon)\,\alpha_i^k. \tag{58}$$

This formula implies that the demand elasticity is bounded between $-\kappa$ for a budget share close to 0 and $-\epsilon$ for a budget close to 1.

Food demand elasticities are a topic that have been studied extensively. A meta-analysis of U.S. price elasticities for food products (Andreyeva et al., 2010) finds mean elasticities between −0.75 and −0.27 (excluding beverages and food away from home). Similar elasticities have been found in a meta-analysis on China (Chen et al., 2016) with elasticities between −0.86 and −0.33. These meta-analyses are based on estimations on household surveys, but the elasticities estimated at the country-level on ICP data by Seale and Regmi (2006) are very close. Based on this literature, we assume $\kappa = 0.6$, which targets the typical elasticity in this literature.

Elasticity of substitution between agricultural products for feed demand We proceed similarly for the elasticity of substitution between agricultural products for feed demand. Let first note that it governs the price elasticity of feed demand. From equations (42) and (43):

$$\frac{\partial \ln x_i^k}{\partial \ln P_i^k} = -\varsigma\left(1 - \alpha_i^{k,\text{feed}}\right). \tag{59}$$

So, feed demand elasticities vary between $-\varsigma$ and 0.

From the literature on the estimation of feed demand, one can note that feed demand elasticities tend to be higher than food demand elasticities, which is consistent with feed choice being more a matter of economic and technical choice rather than a matter of individual preferences as food choice can be. They also vary substantially between sources and between livestock sectors. Beckman et al. (2011) estimate feed demand elasticities on data simulated from a least-cost ration model of the U.S. feed market. Their estimates vary between −1.9 and −0.05, depending on the feed products and the livestock sectors. Peeters and Surry (1993) and Rude and Meilke (2000) estimate feed input demand equations on time-series. On Belgian data, Peeters and Surry (1993) find feed demand elasticities, aggregated over all livestock sectors, to be between −0.79 and −0.21. On European data, Rude and Meilke (2000) find elasticities between −2.13 and −0.32. We follow this literature by assuming $\varsigma = 0.9$.

Elasticity of substitution between varieties For the elasticity of substitution between varieties, we retain the estimation of CDS of 5.4. Since this estimation is also close to what the meta-analysis of Head and Mayer (2014, section 4.2) has found to be the typical trade elasticity ($1 - \sigma_k$ in the model), −5, we retain also 5.4 for the outside good. But, we should note that there is a large variety of estimates in the gravity literature. For example, for agricultural products, Caliendo and Parro's (2015) preferred estimate of the trade elasticity is −9, almost twice as large CDS' estimate, which would lead to even higher trade reallocations.

Degree of within-field heterogeneity From equation (29), θ, the degree of within-field heterogeneity, is the parameter governing the acreage elasticity, a reasonably well studied elasticity in agricultural economics, at least in developed countries and for the most important crops. There is no recent survey on this question. The most recent one (Rao, 1989), thirty years ago, pointed to crop-specific long-run elasticities between 0.3 and 1.2 in developing countries. More recent evidence is available on the acreage elasticities of maize and soybean in the U.S., which have been studied extensively. We adapt and extend in table 3 the table 1 of Miao et al. (2016) that reports these elasticities from different studies. These estimates display a large variability, part of it likely related to the regular changes in farm policies and so farmers' incentives, but they are all below 1 and the most recent estimates have settled on values around 0.3–0.4. From this literature, we target an average world acreage elasticity, weighted by the value of production, of 0.5. To calculate the elasticities, one needs the values of p_i^k/r_i^k, π_i^{fk}, and Q_i^{fk}/Q_i^k. p_i^k/r_i^k is not observed but $p_i^k Q_i^k / r_i^k Q_i^k = 1/\phi_i^{k,\text{land}}$ is available from GTAP database (more on data for calibration below). π_i^{fk} and Q_i^{fk}/Q_i^k can be calculated from the calibrated values of r_i^k as explained in section 3.3. The chosen elasticity target leads to $\theta = 1.1$. For this calibration, the acreage elasticities of maize and soybean in the U.S. are 0.33 and 0.38, respectively, values that are comparable to recent estimates. The sensitivity of the results to the value of θ is assessed in section 6.2.

Table 3: Estimates of acreage elasticities in the U.S. in different studies

Study	Maize	Soybean
Lee and Helmberger (1985)	0.05	0.25
Tegene et al. (1988)	0.20	
Chavas and Holt (1990)	0.15	0.45
Chembezi and Womack (1992)	0.10	
Orazem and Miranowski (1994)	0.10	0.33
Miller and Plantinga (1999)	0.95	0.95
Lin and Dismukes (2007)	0.17–0.35	0.30
Hendricks et al. (2014, long-run elasticities)	0.29	0.26
Miao et al. (2016)	0.45	0.63

4.2 Data for initial equilibrium

4.2.1 Potential land productivity under the current climate and under climate change

For calibrating the potential yields under the current climate and under climate change, we rely on the GAEZ project from IIASA/FAO (2012). This project makes publicly available gridded information at the 5-arcminute level about land resources, climate, land cover, and also about crop statistics and potential yields for 49 crops. Potential yields are calculated for each pixel using a simplified crop growth model that makes use of information on the soil types and climate, and assumed input and water levels. For our initial equilibrium, we use the potential yields calculated from these crop models for the average climate over the period 1961–1990, and called "Baseline" in the GAEZ project. For the yields under climate change, we adopt a 2080s horizon, corresponding to an average of the years 2071–2100, a climate simulated by the UK Met Office Hadley Centre coupled model under the emission scenario A1FI. The scenario

A1FI corresponds to a narrative of rapid economic growth and convergent world with an emphasis on fossil-fuels. It belongs to the set of SRES scenarios (Special Report on Emission Scenarios) developed by the IPCC. These scenarios have been superseded in 2014 by the Representative Concentration Pathways (RCPs) scenarios. The A1FI scenario could be mapped to the more recent RCP8.5. Both are the most pessimistic climate change scenarios with a global average surface warming of 4°C for the A1FI at the end of the 21st century (3.7°C for the more recent RCP8.5), and so the welfare results in this paper should be considered upper bound. However, these scenarios are also the closest ones to the current path of emissions.

The model does not account for different types of land management. So, it cannot make use of the available information in the GAEZ project about input and water levels. Consequently, only the scenario of high inputs under rain-fed conditions is used. The fact that the input levels differ between countries, explaining parts of productivity differences between countries, is implicitly accounted for in the calibration by the insensitivity of the model to a country-crop productivity shifter (Appendix B).

We use in the model all the GAEZ crops that have a corresponding product in FAOSTAT, which excludes only jatropha, pasture legume, miscanthus, switchgrass, and reed canary grass. Grass does not correspond to any FAOSTAT product, but is included here to represent pastures. Some crops are aggregated together to reduce the model size or because they correspond to varieties for which FAOSTAT does not provide separate information. Appendix D provides details about the aggregation procedure and the underlying theoretical assumptions. To put simply, we use the acreage choice equations detailed in section 3.2 and assume that the crops aggregated have the same land rents. Because of the underlying assumption of identical land rents, the aggregation is done only for similar crops. Cassava, sweet potatoes, and yams have been aggregated into the bundle crop “Tropical roots.” Chickpeas, cowpeas, gram, and pigeon peas have been aggregated into “Other pulses.” Foxtail millet and pearl millet have been aggregated into “Millet,” because FAOSTAT does not make the distinction between these varieties. Rice and sugar crops are not aggregated in this way. GAEZ provides potential yield for dryland and wetland rice. Since this distinction corresponds to different production methods and not to varieties, the “Rice” aggregate is constructed by taking the maximum of the two values. Sugar crops, cane and beet, are grown for their sugar content. They are internationally traded once transformed into sugar, but not as raw products. Hence, we convert their potential yields from ton per hectare of sugar crops to ton per hectare of sugar, using that 1 ton of cane yields 0.095 ton of sugar and 1 ton of beet yields 0.144 ton of sugar (based on the average world rate of conversion in FAOSTAT). Then, the aggregate “Sugar crops” is created by taking the maximum of the two values.

Finally, GAEZ crops are mapped to similar crops in FAOSTAT, not just to the exact crops as indicated in the GAEZ documentation. This extended mapping allows us to account for a larger share of agricultural land uses. For example, GAEZ citrus fruits are mapped to all kind of citrus fruits in FAOSTAT, not just oranges. The mapping between crops in the model and crops in GAEZ and FAOSTAT is available in table A2.

Some adjustments to the potential yield data are done. First, under the model assumptions, as long as a field presents a positive potential yield for a crop, this crop will be planted in the field, even if the potential yield is extremely low. To avoid planting crops with unrealistically low productivities, we truncate all potential yields to 5% of the world maximum yield for the corresponding crop, except for grass since it plays the role of the default choice in the model. Second, there is no information on potential yield under climate change for cocoa. Since cocoa tends to be grown in similar agroecological areas as coffee, we use instead the relative changes in the potential yields of coffee. Last, because the Armington assumption for representing trade tends to be conservative with respect to initial trade shares, large yield reduction under climate change can results in very large price movements making finding the new market equilibrium challenging. To avoid this problem, if average country yields are reduced by more than 90%, then the reduction in field-level yields are capped at 10% of the initial yields.

Given the distributional assumption, the potential yields from GAEZ in tons per hectare can be linked to the variable A_i^{fk} in the model. Potential yields are available in GAEZ at the 5-arcminute level. However, they present a degree of high spatial correlation, so there are few benefits from working at such a detail level compared to a more aggregated level as little information is lost with aggregation, but there are high costs associated to the size of the resulting model. In consequence, to reduce the size of the model, we represent fields at the 1-degree level. Average potential yields are calculated from the 5-arcminute level by weighting the original data by the share of land used for agriculture (see next section). Figure 1 represents the relative changes in aggregate potential yields at the field level along with the borders of the regions represented in the model. Crop yields are aggregated according to their contribution to GDP following the first-order welfare approximation of equation (56): $\hat{A}_i^f = \sum_{k \in \mathcal{K}^c} r_i^k Q_i^{fk} \hat{A}_i^{fk} / \sum_{k \in \mathcal{K}^c} r_i^k Q_i^{fk}$. This approach allows to visualize the aggregate first-order effect of climate change on yields. However, being based on a first-order approach it neglects the fact that the loss of productivity of currently cultivated crop may be compensated by the increased productivity of a crop not currently produced. With higher temperatures and longer growing periods, the Northern and Southern-middle latitudes could experience large productivity gain. The tropics would be the most affected regions with very strong reduction in current yields. The Northern middle latitudes would be in between with relative changes closer to 0 and some regions, often mountainous like the Alps or the Himalayas, even displaying gains.

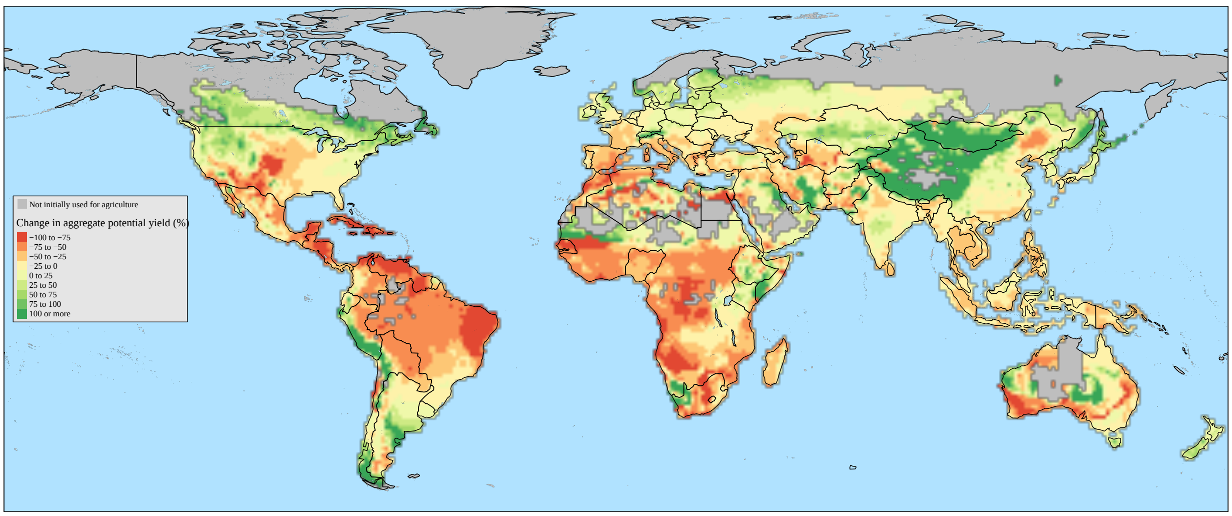

Figure 1: Relative changes in aggregate potential yields. Gray areas indicate areas not used for agriculture in 2007.

4.2.2 Spatial extent of agriculture land

We need information about the share of the cells used for agriculture. This information will be used for two purposes. First, to weight the GAEZ potential yields when they are aggregated at a coarser spatial level. Second, for the model to avoid allocating crops on areas that are currently urbanized, forested, or under other land uses not immediately compatible with agriculture. For this, we use the extension to 2007 of Ramankutty and Foley's (1999) data on agricultural land cover.[5] Ramankutty and Foley (1999) provide gridded information at the 30-arcminute level regarding the share of each cell in cropland or pastures. We add up these shares to obtain the share of agricultural land use.

To determine the surface of each field in the model, we proceed as follows. We overlay each cell of the gridded yield data with countries' borders from Natural Earth data and calculate the surface of the cell in each country. It is possible that a cell is located across borders and so should be allocated to different countries. In such cases, it means in the model that a field f can be shared between several countries, which would all have the same potential yields. However, in each country, the surface s_i^f would be different. We multiply the surfaces obtained by the intersection of the cells and borders with the share of agricultural land use to obtain s_i^f.

This procedure results in 11,801 fields with areas between 100 hectares and 1.2 million hectares, and a median of 0.3 million hectares, depending on the latitude of the fields, their share of agriculture land use, and the intersection with the countries' borders. Of these 11,801 fields, 1,328 are shared between countries. The smallest number of fields

[5]Downloaded from `http://landuse.geog.mcgill.ca/pub/Data/Histlanduse/NetCDF/` on June 29, 2017.

on a country is 12 for the Netherlands, and the highest 1,731 for the region "Rest of Sub-Saharan Africa." From this approach, total agricultural area in the model is 4.12 billion hectares. FAOSTAT indicates an agricultural area of 4.92 billion hectares for 2007 and 4.88 for 2011. Such a large discrepancy is typical of the important uncertainty in global land cover data (Fritz et al., 2011).

4.2.3 Agricultural production, final demand, feed demand, and trade

Most of the other agricultural data come from FAOSTAT. To remove the influence of outliers or the effects of particular weather events, data are taken to be the average over 2010–12. The value of crop production, $p_i^k Q_i^k$ for $k \in \mathcal{K}^c$ and $k \neq g$, comes from the FAOSTAT value of agricultural production database expressed in current million US$. If this information is missing, which occurs if producer prices are missing, then the value of production is estimated by multiplying the produced quantities in tons with the world price. The world price is calculated by averaging producer prices available in other countries weighted by produced quantities.

Trade values, X_{ij}^k for $i \neq j$, $k \in \mathcal{K}^c$ and $k \neq g$, come from FAOSTAT, which aggregates them from COMTRADE to its product nomenclature. By default, we take the value of trade from importers' declaration, but if missing we use the value declared by the exporter. For oil crops, the trade value is the sum of the values for the crops and their derived products (oil and meal). For sugar crops, sugar being traded under various forms, we sum together the trade values of "Sugar raw centrifugal" and "Sugar refined."

The demand of a crop for feed, $P_i^k x_i^k$ for $k \in \mathcal{K}^c$ and $k \neq g$, is calculated using FAOSTAT commodity balances. Commodity balances report in tons the balance sheets of supply (imports and production), demand (processing, food, feed, seed, losses, exports, and other uses), and stock variations of each agricultural product. The monetary value of feed demand is obtained by, first, calculating from the balance sheets the share of feed demand over supply, and, then, by multiplying this share to the monetary value of production and total imports previously calculated. This approach makes the implicit assumption that producer prices and consumer prices are the same which, for this purpose and given that most agricultural products are commodities, is rather innocuous. For some products, such as oilcrops, it is necessary to consider the demand for feed for the products derived from the crop in addition to the crop itself. For example, soybeans are used as feed directly, but 10 times more tons are consumed under the form of soybean meal.

The value of crop final consumption, $P_i^k C_i^k$ for $k \in \mathcal{K}^c$ and $k \neq g$, is calculated simply as the residual, if positive, between the value of production plus the imports minus the demand for feed and the exports. We can also deduce from the value of production and exports the value of domestic trade: $X_{ii}^k = p_i^k Q_i^k - \sum_{j \in \mathcal{I}, j \neq i} X_{ij}^k$.

4.2.4 Other data

The rest of the data comes from the GTAP database version 9.2 with base year 2011 (Aguiar et al., 2016). The value of livestock production is the sum of the value of production in the GTAP sectors "Bovine cattle, sheep and goats, horses" (CTL), "Animal products nec" (OAP), "Raw milk" (RMK), "Wool, silk-worm cocoons" (WOL), "Bovine meat products" (CMT), "Meat products nec" (OMT), and "Dairy products" (MIL) from which is removed the intermediate consumption of the sectors producing primary products that are mostly traded once processed: CTL, OAP, and RMK. The value of livestock trade is the sum of trade in the seven GTAP livestock sectors. Final consumption is calculated as the residual between production and trade.

The share of land in crop production costs, $\phi_i^{k,\text{land}}$ for $k \in \mathcal{K}^c$ and $k \neq g$, is calculated from the corresponding share in GTAP after mapping the model crop to the GTAP sectors. For the value of grass production, we rely on the share of value-added accruing to land in the GTAP sectors CTL, OAP, and RMK, which corresponds to pastures since other sources of feed are accounted as intermediate consumption in the input-output matrix.

Non-agricultural value added, which corresponds in the model to $w_i N_i^0$, is calculated as a residual to target the countries' GDP. Similarly, bilateral trade in the non-agricultural good in calculated as a residual to target total bilateral trade.

The resulting database is not perfectly consistent with a market equilibrium because trade data may be inconsistent with data on production and feed demand resulting in negative values for final consumption. Using a cross-entropy procedure (Golan et al., 1994), the data are adjusted to satisfy an equilibrium, which allows us to calibrate the model on an initial equilibrium.

5 Quantitative results

Before turning to the counterfactual simulations of climate change, we should note that our initial equilibrium data include the trade imbalances observed in the world in 2011. To avoid that these imbalances affect the counterfactual results, we first run a counterfactual simulation to remove them, forcing $\hat{\Delta}_i = 0$. Once this is done, we can proceed with the counterfactual simulations of the effects of climate change.

5.1 Main counterfactual results

The main welfare results are presented in table 4. Column 1 reports the share of crop output in GDP, which will prove useful to interpret welfare results as countries with a high share of GDP devoted to agriculture are more likely to be affected by changes in this sector. Column 2 reports the net agricultural trade as a share of the value of agricultural production ($[\sum_{k\in\mathcal{K}^a}(\sum_{j\in\mathcal{I}} X_{ij}^k - X_i^k)]/\sum_{k\in\mathcal{K}^a} p_i^k Q_i^k$). By measuring the direction of the dependence on foreign markets, this indicator helps interpret the changes in terms-of-trade. Columns 3 to 6 report welfare changes in percentage of GDP and its decomposition following equation (57). Terms-of-trade effects have been separated between non-agricultural and agricultural terms-of-trade effects. The last line reports the average world effect (world indexed w), which for welfare is calculated as

$$\frac{EV_w}{E_w} = \frac{\sum_{i\in\mathcal{I}} EV_i}{E_w}. \tag{60}$$

Terms-of-trade effects of the non-agricultural products (column 3) are in average much lower than the two other components of welfare. Except when very small, these terms-of-trade effects always go in the same direction as the total welfare effects, with a correlation coefficient of 0.95. Countries that gain from climate change have non-agricultural terms-of-trade gains, and conversely. The explanation is as follows: countries experiencing welfare gains because of climate change tend to increase their agricultural exports or reduce their agricultural import demand. In either case, this translates into a real exchange rate appreciation. The smallness of the non-agricultural terms-of-trade effects relative to total welfare changes implies that at as first approximation they can be neglected. They make more precise the welfare changes evaluation, without affecting much the results. We explore this issue deeper in analyzing the effects of the trade modeling assumptions in section 6.3.

Few countries experience gains related to productivity changes (column 5), and when there are gains, they tend to be rather small with a maximum of 0.67 for Argentina. So, for the countries experiencing significant welfare gains from climate change, these gains do not come from increased yields caused by climate change but from improvements in their agricultural terms-of-trade. This appears clearly for Argentina, Ethiopia, or Kenya. Because of the inelasticity of demand for food, the reduction in yields triggered by climate change requires large changes in prices to clear markets and, thus, large terms-of-trade effects. One implication is that the countries that initially export large proportion of their agricultural production (e.g., Argentina, Brazil, Canada, France, United States) tend to gain from climate change, even if they suffer from productivity losses, by shifting through international prices the burden of the adjustment to climate change to consuming countries. The only exception being Central America where productivity losses exceed the terms of trade gains. The opposite is also true: net-food importing countries suffer from terms-of-trade related losses. Countries with large welfare gains are not present in CDS, despite lower global losses, because their elastic demand implies that price adjustments are too small for terms-of-trade effects to compensate the productivity losses.

Because of these various effects, food importing, poor, tropical countries are particularly vulnerable to climate change. Their high share of crops in GDP makes them more sensitive yield shocks. Their reliance on imports exposes

Table 4: Benchmark counterfactual welfare results

Country	Crop output as % of total GDP (1)	Net ag. trade as % of ag. prod (2)	Welfare decomposition (EV as % of GDP)[a] Non ag. terms of trade (3)	Ag. terms of trade (4)	Productivity change (5)	Total (6)
Argentina	8.11	60.07	0.88	12.70	0.67	13.72
Australia	3.56	33.87	0.16	1.72	−0.44	1.44
Bangladesh	15.66	−31.45	−1.76	−14.63	−7.27	−24.25
Brazil	7.60	37.93	0.30	6.92	−3.89	3.29
Canada	3.08	26.03	0.56	2.37	0.50	3.41
China (including Hong Kong)	9.51	−5.19	0.27	0.27	−0.95	−0.41
Colombia	7.19	4.58	−0.32	3.03	−7.28	−4.66
Egypt	8.00	−47.46	−0.56	−6.60	−3.09	−10.37
Ethiopia	48.48	1.32	2.58	34.54	−1.18	34.15
France	3.29	18.81	0.13	0.95	−0.16	0.93
Germany	2.20	−7.64	0.06	−1.04	0.03	−0.94
Greece	6.04	−8.34	−1.39	−6.03	−14.34	−22.37
India	16.81	4.99	−0.50	−1.08	−13.13	−15.00
Indonesia	13.04	−8.03	−0.52	−0.70	−8.92	−10.29
Iran	6.06	−15.73	−0.38	−2.59	−2.16	−5.19
Italy	2.90	−22.90	−0.23	−2.32	−1.51	−4.10
Japan	1.58	−31.94	−0.02	−0.78	−0.11	−0.91
Kazakhstan	9.37	−2.51	0.07	−0.43	−0.58	−0.94
Kenya	25.65	5.78	3.21	30.92	−5.08	28.16
Korea, South	2.28	−49.48	−0.05	−2.04	−0.11	−2.22
Malaysia	8.82	−30.12	−0.27	−10.32	−1.03	−11.66
Mexico	3.87	−16.96	−0.06	−0.31	−1.23	−1.61
Morocco	13.34	−26.41	−1.53	−11.87	−8.53	−22.29
Netherlands	3.40	−18.34	−0.08	−6.96	−0.01	−7.07
Nigeria	10.56	−10.10	−3.09	−7.26	−38.87	−52.42
Pakistan	25.16	2.30	0.60	2.52	−2.24	0.87
Peru	8.50	−7.15	0.19	1.39	−3.76	−2.20
Philippines	13.88	−0.61	−0.15	7.08	−9.85	−3.00
Poland	5.52	2.77	0.14	−0.15	0.19	0.19
Romania	9.72	−1.59	−0.10	−0.29	−0.92	−1.32
Russia	4.56	−10.37	0.04	−0.58	−0.09	−0.63
Senegal	14.73	−42.71	−4.01	−21.22	−10.52	−37.33
South Africa	5.05	1.49	0.13	2.13	−1.62	0.64
Spain	3.82	1.74	0.04	1.26	−1.46	−0.17
Sri Lanka	7.04	−37.53	−1.87	−11.51	−13.46	−27.69
Thailand	8.74	20.34	−0.48	0.32	−6.47	−6.70
Turkey	6.73	−6.59	0.19	0.64	−1.40	−0.58
Ukraine	14.69	30.47	0.26	10.31	−1.86	8.73
United Kingdom	1.75	−36.57	−0.03	−1.03	0.03	−1.04
United States	2.59	16.07	0.09	0.34	−0.23	0.20
Viet Nam	18.00	−1.80	−0.85	0.01	−14.16	−15.14
Caribbean	6.00	−11.07	−1.25	−3.14	−8.47	−13.15
Central America	13.34	19.96	−0.74	13.91	−16.63	−3.61
Rest of Asia	5.85	−15.50	0.11	−0.35	−0.86	−1.10
Rest of Commonwealth of Independent States	14.90	−5.11	0.40	−1.59	0.23	−0.94
Rest of Europe	3.21	−2.60	0.09	−0.31	0.09	−0.12
Rest of Middle East and North Africa	2.96	−72.85	−0.55	−5.30	−1.06	−6.97
Rest of Oceania	11.35	43.35	0.76	5.04	−1.69	4.08
Rest of South America	7.33	7.98	0.03	3.56	−3.19	0.39
Rest of Sub-Saharan Africa	23.06	−1.74	−1.68	2.33	−24.41	−24.31
World	5.04	0	0	0	−1.71	−1.76

Note: [a] From equation (56), the sum of columns 3–5 gives approximately column 6. Decomposition obtained by dividing the yield shocks linearly in 800 shocks. It is almost exact for countries with limited welfare changes, but little discrepancies appear when absolute welfare changes exceed 10%.

them to detrimental terms-of-trade shocks. And their geographical location is the most exposed to the negative effects of climate change on yields. In the model, this concerns for example Bangladesh, Caribbean countries, Malaysia, or Sri Lanka.

We turn now to the specific situation of Sub-Saharan Africa, which is the region experiencing the largest losses with an average loss of -23.17%. One obvious explanation for this large welfare loss is the large decrease in potential yields on some of key African crops such as cocoa and tropical roots, combined with the high share of agriculture in GDP in these countries. But that is not enough to explain these very large welfare losses. A specificity of African agriculture is its reliance on crops that are scarcely traded (and sometimes not at all according to official statistics) such as tropical roots (cassava, sweet potatoes, and yams) or tropical cereals (millet and sorghum), because of perishability or because of the high trade costs in the region (Porteous, 2017). For example, starchy roots contribute to 23% of Nigerian caloric intake with almost no international trade. When the productivity of such a crop is severely hit by climate change, the model leaves little scope of adaptation. Without initial trade, no trade can be created under an Armington structure. Because of the low flexibility of demand, domestic prices increase a lot, driving up the planted areas despite the lower productivity, which aggravates the severity of the initial shock as more resources are pulled inside a sector with now a very low productivity. Things would have played out differently with enough initial trade: acreage in tropical roots would have been reduced and the country would have specialized in other productions and relied more on imports. With large welfare gains, Ethiopia and Kenya are two exceptions, which were already visible in figure 1 where these countries are part of the small African regions experiencing yield gains in average. For the other African countries, the lack of international trade aggravates the productivity loss by preventing reallocations on more profitable crops (this claim is proved in section 6.3).

To illustrate the role that international trade will play in the adaptation to climate change, figure 2 plots the changes caused by climate change in the export shares in total trade of the main cereals, maize, rice, and wheat. Shares in world trade vary greatly with climate change to the extent that for maize and rice they bear little resemblance to the current market shares. For the maize market, traditional exporters such as the U.S., Brazil, France, and Ukraine suffers strong yield reduction and reduce their exports in consequence. Canada, Germany, and China, being located in northern latitudes, have higher maize yields and step in to fill the gap, the world production of maize increasing even by 19%. The effects are similar for rice. The traditional rice exporters are tropical countries that are severely hit by climate change. Rice production moves north, and new exporters emerge: China, Korea, and Japan. The export shares in the wheat market change less with decreases in some traditional exporters (Argentina, Australia, France, United States) and increases in others, located in Northern latitudes (Canada, Germany, Russia). The pattern of international trade flows in agricultural products may look extremely different from now because of the effects of climate change.

5.2 Aggregate yield shocks

To better understand how changes in potential yields affect acreages, trade, and welfare, we decompose the yield shocks into different components and apply them separately. We start by applying to each field the average global change in potential yields. To be able to average yield shocks from different crops, we need a weighting scheme. We use the welfare metric and calculate the average shock by weighting each field-level shock by its first-order welfare contribution: $\hat{A} = \sum_{i\in\mathcal{I},f\in\mathcal{F}_i,k\in\mathcal{K}^c} r_i^k Q_i^{fk} \hat{A}_i^{fk} / \sum_{i\in\mathcal{I},f\in\mathcal{F}_i,k\in\mathcal{K}^c} r_i^k Q_i^{fk}$. Calculated in this way, the global average yield shock due to climate change is -13.2%. The new counterfactual potential yields are then calculated as

$$A_i^{fk\prime} = \hat{A} A_i^{fk}. \tag{61}$$

The other counterfactual simulations with aggregate shocks are for the average yield shocks at the country level, at the crop level, and at the country-crop level, with the averages calculated as above. Table 5 reports the results of these simulations.

This way of aggregating yields shocks present two limits that should be understood. First, since the weights used

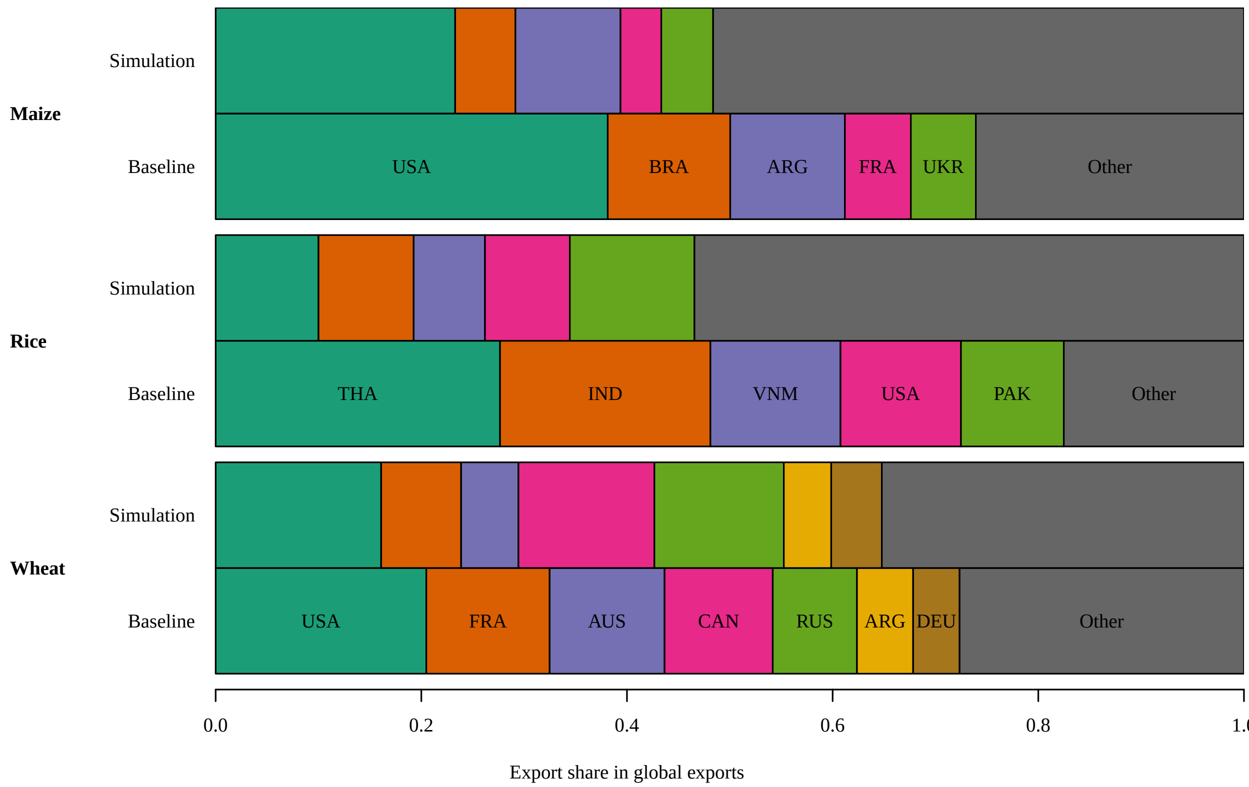

Figure 2: Changes in export shares

Table 5: Results under various counterfactual aggregate yield shocks (percentage change)

Variable	World average (1)	Country average (2)	Crop average (3)	Country-crop average (4)	Benchmark without new crop on fields (5)	Benchmark (6)
Welfare change						
Asia	−0.97	−0.86	−4.50	−7.02	−6.40	−3.09
Commonwealth of Independent States	−0.04	0.35	−3.41	0.11	0.17	−0.08
Europe	−0.26	−0.45	−3.46	−3.23	−2.96	−1.35
Latin America	1.18	0.27	6.30	4.54	4.26	1.35
Middle East and North Africa	−1.68	−3.00	−11.45	−13.61	−12.57	−6.08
Northern America	0.36	0.54	1.16	1.56	1.43	0.53
Oceania	0.98	1.30	3.67	4.76	4.39	1.78
Sub-Saharan Africa	−1.19	−9.34	−19.46	−33.06	−31.84	−23.17
World	−0.25	−0.53	−2.46	−3.40	−3.14	−1.76
MAD of acreage shares	26.85	31.89	37.81	40.37	60.87	63.81
MAD of between-country acreage shares	25.81	30.88	36.53	39.02	34.25	41.73
MAD of international trade volumes	16.10	50.55	49.45	68.28	68.88	103.34

to aggregate yield shocks are based on a first-order approximation based on the baseline equilibrium values, they do not account for the fact that the economic weight of each crop and each field changes with climate change. Second, since equation (61) is multiplicative in the initial yields, it cannot account for couples field-crop where productivity was initially zero and becomes positive after climate change. To make things comparable, table 5 reports the benchmark results in column 6 but also the benchmark where this extensive margin is shut down in column 5. Comparing the last two columns shows that allowing new crops on fields has a huge impact. Climate change will reduce the productivity in many fields but will also make possible new production, reducing by one-fourth the global welfare losses.

To save on space, welfare results are reported for regional aggregates (defined in table A1). The amount of changes in acreages and in trade flows are assessed using measures of mean absolute deviation (MAD), reported in the last three rows. For acreages, it is calculated on acreage shares weighted by initial areas:

$$\text{MAD of acreage shares} = \frac{\sum_{i\in\mathcal{I},f\in\mathcal{F}_i,k\in\mathcal{K}^c} s_i^f \pi_i^{fk} \left|\hat{\pi}_i^{fk} - 1\right|}{\sum_{i\in\mathcal{I},f\in\mathcal{F}_i,k\in\mathcal{K}^c} s_i^f \pi_i^{fk}}. \tag{62}$$

It represents the average absolute percentage change in crop acreages. Another interesting measure of changes in acreages is the between-country changes that considers only the acreage changes aggregated at the country-level:

$$\text{MAD of between-country acreage shares} = \frac{\sum_{i\in\mathcal{I},k\in\mathcal{K}^c} \left(\sum_{f\in\mathcal{F}_i} s_i^f \pi_i^{fk}\right) \left|\hat{\pi}_i^{k} - 1\right|}{\sum_{i\in\mathcal{I},f\in\mathcal{F}_i,k\in\mathcal{K}^c} s_i^f \pi_i^{fk}}, \tag{63}$$

with $\pi_i^k \equiv \sum_{f\in\mathcal{F}_i} s_i^f \pi_i^{fk} / \sum_{f\in\mathcal{F}_i} s_i^f$. For trade flows, we weight the change in the volume of trade by the initial trade value:

$$\text{MAD of international trade volumes} = \frac{\sum_{i,j\in\mathcal{I},i\neq j,k\in\mathcal{K}^c} X_{ji}^k \left|\hat{X}_{ji}^k / \hat{p}_j^k - 1\right|}{\sum_{i,j\in\mathcal{I},i\neq j,k\in\mathcal{K}^c} X_{ji}^k}. \tag{64}$$

It represents the average absolute percentage change in trade volumes.

From column 1 to 5, the world is exposed to the same aggregate yield shock but applied differently across the columns. Depending on how the yield shock is applied, it has dramatically different effects. If the shock is uniform across countries, the global welfare losses are the lowest. Under this configuration, climate change is much less costly for countries from Middle East and North Africa and Sub-Saharan Africa. Despite a uniformly negative shock, the three regions that win from climate change in the benchmark still win because of their terms-of-trade gains. Because the shock is the same, prices tend to move similarly everywhere, which induces much less trade changes than in other scenarios.

In the second column, the shock is specific to each country and therefore affects the countries' comparative advantages in crop production. One mechanism explains the higher welfare losses compared to a uniform shock. The shock now affects countries differentially, but countries do not have the same capacity to adapt to the shock. In this model, one of the key adaptation mechanisms is international trade. From equation (44), the change in consumer prices is a power mean of import prices weighted by initial trade shares. If the initial trade shares are small, the consumer price is very dependent on the domestic producer price, which increases a lot in case of adverse shock if there are no exports to reduce. Sub-Saharan Africa is both exposed to a larger shock than the mean but is also less connected through international trade, so less able to adapt to the shock, which aggravates the mean effect.

In column 3, the shock is specific to each crop but affects countries similarly. So, it affects the countries' comparative advantages only because their initial crop specialization differs. This creates less trade opportunities than a country-specific shock given that a crop is affected uniformly everywhere, but it leads to more acreage reallocations. The same mechanism operates to explain the different welfare gains: some crops tends to create more welfare losses than others because of the lack of adaptation through trade.

The column 4 of table 5 reports the results where for each couple field-crop the average country-crop shock is applied. This is the closer shock to the real one. This shock is also similar to what would be obtained with a model with one field per country, since it neglects all within-country changes. In this case, comparative advantages change between countries and for all crops, but without within country differentiation, except for the initial field heterogeneity. This is the scenario with the highest global welfare losses, highest even than in the benchmark without new crops. Comparing the last rows on columns 4 and 5 shows that having shocks that are heterogeneous within countries affects little the amount of change in international trade volumes, consistent with the idea that between the two columns countries should have the same comparative advantages. In column 5, more adjustments take place on the supply side with much more changes in acreages allowed by the within-country heterogeneity.

In the absence of within-country heterogeneity in the climate-change shock (columns 1–4), the acreage adjustments take mostly place between-country, with negligible within-country adjustments. With within-country shock heterogeneity (columns 5–6), the share of within country adjustments increases to close to one-third.

6 Role of each adjustment margin

In this section, we analyze the contribution to adaption to climate change of each adjustment margin. We do this by varying the flexibility of each margin, which also makes clear the inner workings of the model as well as the mechanisms that trigger more or less international trade adjustments. Beyond this objective, this section helps also assess the sensitivity of the results to the behavioral parameters and to some of the modeling assumptions.

6.1 Demand

Price elasticity of agricultural good demand To understand the role of the price elasticity of agricultural good demand, we repeat the counterfactual analysis with different values. We consider an elasticity ϵ of 0.5, a value that could be found in poor populations as discussed in section 4.1; an elasticity of 1 as implicitly adopted in CDS, a value that should be considered an upper bound as it slightly exceeds what can be found in the literature even for the poorest populations; and an elasticity varying with per capita GDP. In this last case, we assume that the elasticity evolves linearly with the logarithm of per capita GDP. We assign all elasticities by assuming that the country with the highest per capita GDP, Australia, has an elasticity of 0.05 and by targeting an average world elasticity equal to the benchmark value of 0.2, with each country elasticity weighted by its initial value of agricultural good demand. With these assumptions, the poorest country, Ethiopia, has an elasticity of 0.46 and a country such as India has an elasticity of 0.35.

Table 6 presents some of the key results for alternative values of ϵ. In addition to the statistics reported in previous tables, table 6 reports the change in agricultural good consumption, at regional and world level, and in agricultural good price at the world level. These statistics are calculated as base-weighted Laspeyres quantity and price indexes of the country-level variables $\hat{C}_i$ and $\hat{P}_i$. Welfare losses decrease with a more elastic demand. However, these welfare results are not straightforward to interpret in conjunction with the result that agricultural consumptions also decrease much more with a more elastic demand, which intuitively if thinking in terms of nutrition should be associated with higher welfare losses. Given that the demand system does not give any specific role to food, a more elastic demand also implies a welfare less reactive to changes in agricultural-good consumption, and any effects of reduced consumption on health, nutrition, and therefore human capital is neglected.

For higher values of ϵ, adjustments take place much more at the final consumption level rather than at the price level. Instead of a 185% increase of the agricultural price in the benchmark, $\epsilon = 1$ leads to a 35% increase. Less price adjustments means less terms-of-trade effects, and so no region gains from climate change (although a few countries still gain because of the productivity gains). Varying the final demand elasticity influences trade adjustments, with a mean absolute deviation of international trade volumes reduced by 40% for $\epsilon = 1$. The climate change induced yield change constitutes a large change in comparative advantages and this shock is the same whatever the assumptions on elasticities. However, prices have to provide the incentives for this change in comparative advantages to translate into large changes in trade volumes. When demand is elastic, the climate change shock is absorbed largely by adjustments in final consumption, prices react much less than in benchmark creating less incentives for trade to reallocate.

The last column reports the results in the case where ϵ is a function of the initial per capita GDP. Our benchmark calibration was parsimonious with the same elasticity for all countries, but this variant with a demand elasticity decreasing with income may be more consistent with the evidence and allows us to discuss how countries share

Table 6: Effects of the price elasticity of agricultural good demand (percentage change)

Variable	Benchmark $\epsilon = 0.2$ (1)	$\epsilon = 0.5$ (2)	$\epsilon = 1$ (3)	ϵ function of GDP per cap. (4)
Welfare change				
Asia	−3.09	−1.72	−1.27	−2.47
Commonwealth of Independent States	−0.08	−0.68	−0.69	−0.45
Europe	−1.35	−0.79	−0.57	−1.69
Latin America	1.35	0.16	−0.10	1.14
Middle East and North Africa	−6.08	−2.48	−1.42	−5.44
Northern America	0.53	−0.13	−0.23	0.29
Oceania	1.78	0.28	−0.04	1.31
Sub-Saharan Africa	−23.17	−6.99	−3.34	−10.71
World	−1.76	−1.01	−0.74	−1.49
Agricultural good consumption				
Asia	−15.76	−18.94	−21.76	−17.73
Commonwealth of Independent States	−13.22	−14.71	−16.32	−12.65
Europe	−15.94	−19.24	−23.11	−7.94
Latin America	−18.50	−24.36	−30.63	−17.85
Middle East and North Africa	−18.95	−23.52	−28.19	−18.50
Northern America	−12.37	−13.62	−15.54	−4.25
Oceania	−13.06	−15.25	−18.66	−5.94
Sub-Saharan Africa	−29.91	−38.28	−44.40	−38.73
World	−16.65	−20.22	−23.72	−15.71
Agricultural good price	185.14	66.55	35.35	148.33
MAD of acreage shares	63.81	64.47	67.74	63.83
MAD of international trade volumes	103.34	70.34	60.70	89.19

the burden of adaptation to climate change. In this variant, developed regions experience small reductions in their agricultural good demand because they have very low demand elasticities. The opposite is true in Sub-Saharan Africa where the reduction of consumption is much larger than in the benchmark. Once again, it seems that the effects of climate change compound with existing economic difficulties. Tropical countries will be hit hardest by climate change, but they are also poorer than the rest of the world and therefore more susceptible to adjust their agricultural consumption to higher prices than it is the case in richer countries. In rich countries, agricultural products represent a small share of their expenditures and so consumers are little responsive to increased prices. Their lack of demand adjustments fuels in turn the increase of global prices, which trigger demand adjustments elsewhere in the world where consumers have a consumption that is more sensitive to prices. Thus, poor countries have to support a disproportionate part of the demand adjustments to climate change.

Final demand elasticity of substitution between agricultural products In our baseline model, the elasticity of substitution between agricultural products for food is calibrated at 0.6, consistent with the widespread estimations of inelastic demand for food products. While the literature on food demand mentioned in section 4.1 robustly finds inelastic food demand with elasticities that rarely exceed 1 in absolute value, this literature is mostly concerned with short-run elasticities, even if short run is understood as annual. When considering the effects of climate change and neglecting the transitional dynamics to the 2080s, we are interested in long-run elasticities, but to our knowledge, these have not been studied. In two papers, Atkin (2013, 2016) touches on this issue by showing that food demand is affected by habit formation and how habits could affect the nutritional effects of trade liberalization and migration. Tastes for certain foods evolve depending on how much they were consumed in the past, especially as a child, and so, depending on their past prices. This mechanism would point toward higher demand elasticities in the long run than in the short run as tastes gradually evolve toward the foods that are the cheapest locally. However, Atkin (2013) also notes that tastes evolve slowly with a doubling in the price of a staple a decade earlier reducing the budget share of that food by between 3 and 5%. And this slow adjustment is in the context of poor Indian households that could be expected to have higher food demand elasticities, and so a higher propensity to tastes adjustment, than affluent households in rich countries where the budget share of primary products is small.

To explore the quantitative importance of this possibility of a higher long-run substitution between food products, we consider in column 3 of table 7 a scenario with an elasticity of substitution of 1.2, the double of the benchmark value. We also report in column 1 the results with an elasticity lower than benchmark and in column 4 the results with the elasticity used in CDS: 2.82. This substitution elasticity plays a key role. With more substitution between food products, climate change is much less costly given that not all food products are affected alike, some even showing higher potential yields under climate change. In turn, it implies a lower decrease of food consumption, in opposition to what is observed in table 6 for the elasticity of total food intakes, because consumers adjust more easily their diet to the cheapest food. A higher elasticity of substitution reduces also a lot the changes in trade volumes, but these changes remain sizable even under CDS elasticity with a mean absolute deviation of 72%, because even if consumers are more susceptible to change their diet, their country agricultural production may still be affected a lot by climate change, and international trade is required to fill the gap between domestic demand and supply.

Table 7: Effects of the elasticity of substitution between food products (percentage change)

Variable	$\kappa = 0.4$ (1)	Benchmark $\kappa = 0.6$ (2)	$\kappa = 1.2$ (3)	$\kappa = 2.82$ (4)
Welfare change				
Asia	−7.24	−3.09	−1.16	−0.47
Commonwealth of Independent States	−1.59	−0.08	0.05	0.07
Europe	−4.99	−1.35	−0.36	−0.14
Latin America	4.65	1.35	0.17	−0.16
Middle East and North Africa	−12.21	−6.08	−2.53	−1.17
Northern America	0.09	0.53	0.29	0.13
Oceania	3.73	1.78	0.73	0.34
Sub-Saharan Africa	−23.45	−23.17	−10.72	−5.84
World	−4.08	−1.76	−0.68	−0.33
Agricultural good consumption	−26.63	−16.65	−8.16	−3.87
Agricultural good price	615.46	185.14	59.71	24.20
MAD of acreage shares	71.91	63.81	56.09	51.04
MAD of international trade volumes	118.67	103.34	81.74	72.05

6.2 Supply

Acreage choice The role of acreage changes in adaptation to climate change is evaluated in two ways. First, we follow CDS and consider a scenario where acreages cannot adjust and are fixed to their initial values. In this case, following CDS, the counterfactual production is given by

$$Q_i^{k\prime} = \sum_{f \in \mathcal{F}_i} s_i^f \pi_i^{fk} \, \mathrm{E}\left[A_i^{fk\prime}(\omega) \,|\, r_i^k A_i^{fk}(\omega) \in \arg\max_{l \in \mathcal{K}^c} r_i^l A_i^{fl}(\omega) \right], \tag{65}$$

which using that $A_i^{fk\prime}(\omega) = A_i^{fk}(\omega)\, A_i^{fk\prime}/A_i^{fk}$ gives

$$Q_i^{k\prime} = \sum_{f\in\mathcal{F}_i} s_i^f A_i^{fk\prime} \left(\pi_i^{fk}\right)^{(\theta-1)/\theta}, \tag{66}$$

and in exact hat algebra

$$\hat{Q}_i^k = \sum_{f\in\mathcal{F}_i} \hat{A}_i^{fk} \frac{Q_i^{fk}}{Q_i^k}. \tag{67}$$

Second, we vary the acreage elasticity around its benchmark value, halving and doubling it. Since the acreage elasticity is proportional to $\theta - 1$, halving it means decreasing θ to 1.05 and doubling it increasing θ to 1.2. Corresponding to these values, the acreage elasticity of maize and soybean in the U.S. are 0.17 and 0.19 for the lower θ, and 0.66 and 0.75 for the higher. When the value of θ is changed the calibration of the initial rents should be done for the new value according to equation (50). The aggregate values of production, trade or final demand stay the same, but a different θ implies different initial land rents and so different field acreages.

Table 8 reports the results of this exercise, with in the first column the scenario without acreage adjustment. The counterfactual without adjustment in acreages implies also a situation where crops with zero initial potential yields in a field stays non-planted after climate change even if they now have positive potential yields. So, to understand the difference between this scenario and the benchmark, it is interesting to use as an intermediary step the benchmark without any new crop on fields, which is displayed in column 2. Preventing new crops to be planted increases the welfare losses of climate change by 78% with respect to the benchmark. Going one step further and preventing all acreage adjustment increases further the losses but less than preventing new crops. These different welfare losses illustrate the crucial role of acreage changes in adaptation to climate change, with the most important adaptation being the possibility to plant crops that could not grow before climate change.

Table 8: Effects of the assumptions about acreage changes (percentage change)

Variable	No acreage adjustment (1)	Benchmark without new crop on fields (2)	Half acreage elasticity $\theta = 1.05$ (3)	Benchmark $\theta = 1.1$ (4)	Double acreage elasticity $\theta = 1.2$ (5)
Welfare change					
Asia	−7.80	−6.40	−3.32	−3.09	−2.72
Commonwealth of Independent States	0.25	0.17	−0.09	−0.08	−0.07
Europe	−3.76	−2.96	−1.47	−1.35	−1.16
Latin America	5.16	4.26	1.45	1.35	1.18
Middle East and North Africa	−15.52	−12.57	−6.54	−6.08	−5.34
Northern America	1.79	1.43	0.58	0.53	0.46
Oceania	5.18	4.39	1.87	1.78	1.62
Sub-Saharan Africa	−36.96	−31.84	−24.45	−23.17	−21.02
World	−3.83	−3.14	−1.89	−1.76	−1.56
Agricultural good consumption	−29.02	−26.49	−17.29	−16.65	−15.55
Agricultural good price	515.77	414.19	198.07	185.14	164.37
MAD of acreage shares	13.24	60.87	64.04	63.81	63.56
MAD of international trade volumes	69.55	68.88	106.14	103.34	98.99

Varying the degree of within-field heterogeneity from 1.05 to 1.2 influences welfare changes, with lower aggregate losses for higher θ and lower terms-of-trade effects, which materialize in lower gains for the net-exporting regions. Despite the large variations that it implies in the supply elasticities, the welfare changes remain modest compared to column 1 where acreage choices are maintained fixed. This could point to a nonlinear relationship between welfare and the acreage elasticity, when the acreage elasticity becomes very small.

A similar nonlinear relationship may be at play for the interactions between supply and international trade, where two effects go in opposite directions. The less flexible is domestic supply, the wider the imbalances between domestic supply and demand, which would call for more international trade to reduce the imbalances. In this sense, acreage changes and international trade changes are substitutes. On the other hand, if domestic supply is little flexible, then the changes in comparative advantages do not translate well into changes in specialization, limiting the trade adjustments. This points to a complementarity between adjustments in production and adjustments in trade: one is made possible by the other. For the changes in the acreage elasticity, it seems that the substitution effect dominates and trade increases when the elasticity decreases. For the more radical changes of either preventing the planting of new crops or freezing acreage adjustments, trade changes are less important than in the benchmark and the complementarity dominates.

Yield elasticity For the sake of parsimony and because of the difficulty to obtain reliable estimates of yield elasticities at the world level, we have assumed inelastic yields in the benchmark model. However, in addition to changing acreages, intensifying crop production could be a strategy to adapt to climate change. The increase in agricultural prices caused by climate change could make profitable increasing inputs used for crop production. Such a reaction is likely to be heterogeneous across fields, countries, and crops depending among other things on the existing gaps with respect to maximum yields. For this sensitivity analysis, we abstract from this complexity by assuming that yields can be expressed as isoelastic functions of input levels (the outside good being used as input), using the same elasticity η of for all crops and all countries. Appendix E details the changes to be made to the model to accommodate elastic yields. The model with elastic yields nests the benchmark model when yields are assumed to be inelastic, which corresponds to $\eta = 0$. Having elastic yields decreases the acreage elasticities for the same θ. So, to maintain the same elasticities as in the benchmark model, the degree of within-field heterogeneity is taken equal to $\tilde{\theta} = \theta + \eta/(1 - \eta)$, where θ is the benchmark value.

The debates about the indirect land-use changes caused by biofuel policies revolved a lot around the price elasticity of yields given that more elastic yields imply less land-use changes and so less carbon emissions from planting crops on new lands. Berry (2011) and Berry and Schlenker (2011) argue that GTAP-based models use too large yield-price elasticities and that credible estimates are often not significant. Based on their review and some IV estimations, they consider that these elasticities should not exceed 0.1 for the main U.S. crops. Recent estimates in Scott (2013) and Haile et al. (2016) confirm this order of magnitude, while Miao et al. (2016) find a non-significant yield-price elasticity for U.S. soybean and an elasticity around 0.25 for U.S. maize, 0.25 being also the high value used in GTAP models and criticized by Berry (2011). Table 9 reports the counterfactual results with elastic yields assuming $\eta = 0.02$, 0.04, and 0.06, which correspond to yield-price elasticities for U.S. maize of 0.11, 0.21, and 0.33. With $\eta = 0.06$, column 4 corresponds to a situation where the yield-price elasticities are not far from the acreage-price elasticities, an extreme calibration according to this literature.

Having elastic yields increases the total supply elasticity and, thus, the extent of supply-side adaptations, reducing welfare losses. With more supply, agricultural good consumption decreases less and agricultural prices increase less also. It barely affects the amount of changes in acreage shares, which adjust slightly less. Since elastic yields improve the supply-side adaptation, they reduce the imbalances created by climate change and reduce the amount of changes in agricultural trade volumes, showing the same substitution between supply and trade shown in table 8 when changing the acreage elasticity. However, if we focus on the calibration of column 2, which has the most empirical support, elastic yields are not susceptible to change any of the previous conclusions, the amount of change in international trade volumes remaining very high.

Feed demand elasticity of substitution between agricultural products The literature on feed demand elasticities is limited and displays a lot of variations from −0.05 to −2.13 according to the papers reviewed previously. Since demand for feed is unlikely to be as inelastic as food demand, we use the elasticity of substitution between agricultural products for final demand as lower bound in the sensitivity analysis. For the upper bound, we consider the double of

Table 9: Effects of the assumptions about the elasticities of yields and crop substitution for feed (percentage change)

	Benchmark	Elastic yields			Feed substitution	
Variable	$\eta = 0, \varsigma = 0.9$ (1)	$\eta = 0.02$ (2)	$\eta = 0.04$ (3)	$\eta = 0.06$ (4)	$\varsigma = 0.6$ (5)	$\varsigma = 1.8$ (6)
Welfare change						
Asia	−3.09	−2.67	−2.37	−2.14	−3.36	−2.69
Commonwealth of Independent States	−0.08	−0.24	−0.33	−0.38	0.05	−0.26
Europe	−1.35	−1.13	−0.98	−0.86	−1.44	−1.24
Latin America	1.35	0.95	0.68	0.48	1.55	1.07
Middle East and North Africa	−6.08	−4.73	−3.82	−3.19	−6.82	−4.99
Northern America	0.53	0.29	0.14	0.04	0.69	0.31
Oceania	1.78	1.29	0.96	0.74	2.03	1.38
Sub-Saharan Africa	−23.17	−18.02	−14.53	−12.04	−24.41	−21.18
World	−1.76	−1.51	−1.33	−1.20	−1.87	−1.61
Agricultural good consumption	−16.65	−14.15	−12.23	−10.74	−17.78	−14.93
Agricultural good price	185.14	140.98	112.11	92.09	204.13	159.12
MAD of acreage shares	63.81	63.59	63.20	62.70	62.76	65.04
MAD of international trade volumes	103.34	95.67	90.00	85.74	102.96	105.68

the benchmark elasticity, which would put the feed demand elasticities in the high end of the literature. Columns 5 and 6 of table 9 report the results for these alternative values. As expected, a more elastic demand for feed implies less welfare losses and less reduction in agricultural good consumption associated to a limited price increase. The amount of changes in international trade volume is almost insensitive to this parameter, with only a slight increase in changes associated with a higher elasticity. There are likely two opposite effects going on. Increasing the elasticity of substitution between feed crops implies that livestock feed will be more reactive to price change, which should reduce domestic imbalances and the trade changes. But, on the other hand, increasing ς lowers the total cost of feed by allowing more use of the cheaper crops, this in turn leads to a lower price for livestock products and a higher demand. Finally, the higher demand for livestock products requires more import of crops for feed. This latter effect seems to dominate and trade adjustments increase with the elasticity. While this parameter is important for welfare results, it does not seem to affect significantly land-use and international adjustments.

6.3 International trade

When analyzing the role that adjustments to international trade patterns may play in alleviating the consequences of climate change, we can note that there are various ways in which trade adjusts and so various legitimate counterfactual exercises to capture its role. We could consider restricting the adjustments in bilateral import shares, bilateral export shares (or total export shares as in CDS), or the changes in trade flows (volume or values). This is in contrast with the role of acreages changes that can be captured by simply fixing the initial acreages. So, we use different counterfactuals to measure the role of trade. On the one hand, to see how costlier would be climate change if trade changes are limited, we restrict trade adjustments through two approaches. One approach follows CDS and fixes the shares of exports for agricultural goods to their initial values. This is imposed by the following equation that states that changes in domestic trade are proportional to changes in domestic production:

$$\hat{X}_{ii}^k / \hat{p}_i^k = \hat{Q}_i^k \text{ for all } k \in \mathcal{K}^a. \quad (68)$$

This equation holds by adding to the model ad-valorem export taxes (or subsidies), denoted δ_i^k. Three of the model equations have to be adjusted accordingly: equation (44) that defines the consumer price index,

$$\hat{P}_i^k = \left[\sum_{j \in \mathcal{I}} \alpha_{ji}^k \left(\hat{\delta}_j^k \hat{p}_j^k \right)^{1-\sigma_k} \right]^{1/(1-\sigma_k)}; \tag{69}$$

equation (46) that defines bilateral imports,

$$\hat{X}_{ji}^k = \left(\hat{\delta}_j^k \hat{p}_j^k / \hat{P}_i^k \right)^{1-\sigma_k} \hat{X}_i^k; \tag{70}$$

and equation (49) that defines the representative agents budget constraint and where the tax revenues now appear as a lump sum transfer,

$$E_i \hat{E}_i = w_i N_i \hat{w}_i + \sum_{k \in \mathcal{K}^c} R_i^k \hat{r}_i^k \hat{Q}_i^k + \sum_{k \in \mathcal{K}^a, j \in \mathcal{I}, j \neq i} \left(\hat{\delta}_i^k - 1 \right) \frac{X_{ij}^k \hat{X}_{ij}^k}{\hat{\delta}_i^k}. \tag{71}$$

Another approach to restrict trade adjustments is to fix the bilateral import shares to their initial values. This is done by setting the Armington elasticity of substitution equal to 1 for all tradable agricultural products. In this case, the consumer price index equation becomes

$$\hat{P}_i^k = \prod_{j \in \mathcal{I}} \left(\hat{p}_j^k \right)^{\alpha_{ji}^k}. \tag{72}$$

Given the model Armington structure, fixing the bilateral trade shares is symmetric to what has be done for land by fixing the acreage shares.

On the other hand, we consider opposite counterfactuals: what would happen if trade was more responsive to price changes? First, we increase the Armington elasticity for agricultural products to the value estimated in Caliendo and Parro (2015), $\sigma_{k \in \mathcal{K}^a} = 10$, almost twice the benchmark value from CDS. Second, we consider a situation of integrated world market, which can be considered as an upper bound of what international trade can contribute to adaptation to climate change, because it amounts to neglecting all trade costs and preferences for varieties associated with countries of origin. Many agricultural products are actually commodities with very little differentiation regarding what is produced between countries. In such a case, which is not relevant for all agricultural products (e.g., livestock), the Armington assumption we have adopted for convenience may be unduly restrictive and the hypothesis of homogeneous goods would be more appropriate (as adopted for crops by Sotelo, 2015). Properly modeling international trade in homogeneous goods is costly because of the need for extensive data on trade costs and the accounting in the model for all possible trade flows, even if initially null. So, we adopt the hypothesis of integrated world markets without trade costs, which simplifies the modeling of homogeneous products for this exercise and provides an upper bound for a model with trade costs. All products are assumed perfectly integrated, except grass which remains non-tradable (but its price is pinned down in each country by the world price of livestock). We discuss below the changes to be made to have integrated world markets in the model. We also consider an intermediate case where only the non-agricultural good is assumed to be in an integrated world market. This case allows us to evaluate the contribution of the resistances to trade outside agriculture to welfare changes.

The changes to be made to the model to transform it to a model with integrated world markets are relatively simple: bilateral trade variables (X_{ji}^k) are removed as they are now irrelevant, consumer prices and producer prices are equal ($P_i^k = p_i^k = p^k$), and market clearing equations for consumer prices (45) and producer prices (47) are collapsed and summed over all countries. The price of the non-agricultural good is the same over the world and equal to wages, and serves as numeraire in the model. Only one model change is less obvious. Because of the Armington assumption, in the benchmark model a crop is always produced in a country as long as there are positive potential yields. This is no longer the case if products are assumed homogeneous, so we need to account for the possibility of some land rents (and so production) being zero under climate change but positive in the baseline. This is done by expressing equation (36) for crops as a complementarity slackness condition:

$$\hat{r}_i^k \geq 0 \perp \hat{r}_i^k \geq \left(\hat{p}^k - \phi_i^{k,\text{labor}}\right) / \phi_i^{k,\text{land}}. \quad (73)$$

Since wages serve as numeraire and are constant under an integrated world market, changes in land rents completely follow changes in the corresponding world prices. We allow for the possibility of a land rent becoming zero in the counterfactual but not for the opposite situation of a land rent becoming positive after being zero. Because of equation (73), the model with integrated world markets is solved numerically as a mixed complementarity problem using the solver PATH.

Table 10 reports the results of the effects of the assumptions about international trade. Columns are organized from the most responsive trade in column 1 to the least responsive in column 6. If all markets except grass are integrated, global welfare losses are reduced by one-third going from 1.76% to 0.58%. The reduction is especially strong for Sub-Saharan Africa, which suffers a 0.63% welfare loss instead of a 23.17% one. This demonstrates that one of the main reasons of the large welfare losses in Africa in the benchmark model is the low tradability of some of its key agricultural commodities (roots or coarse grains) and its high trade costs. Northern America which enjoys in the benchmark welfare gains because of terms-of-trade gains in agricultural products is now barely affected in welfare terms by climate change as agricultural prices and the associated terms-of-trade evolve much less under integrated world markets.

Table 10: Effects of the assumptions about international trade (percentage change)

Variable	Integrated world markets (1)	Integrated world market in non-ag. (2)	$\sigma_{k\in\mathcal{K}^a} = 10$ (3)	Benchmark $\sigma_{k\in\mathcal{K}^a} = 5.4$ (4)	$\sigma_{k\in\mathcal{K}^a} = 1$ (5)	Fixed export shares (6)
Welfare change						
Asia	−0.98	−3.08	−2.28	−3.09	−5.51	−4.18
Commonwealth of Independent States	−0.34	−0.15	−0.13	−0.08	−1.59	0.35
Europe	−0.77	−1.35	−1.12	−1.35	−2.91	−1.40
Latin America	0.46	1.36	0.82	1.35	4.97	1.95
Middle East and North Africa	−2.16	−5.68	−4.77	−6.08	−12.32	−8.81
Northern America	−0.00	0.41	0.40	0.53	0.69	0.93
Oceania	0.45	1.58	1.28	1.78	3.51	2.87
Sub-Saharan Africa	−0.63	−21.10	−16.55	−23.17	−50.69	−31.16
World	−0.58	−1.73	−1.35	−1.76	−3.45	−2.22
Agricultural good consumption	−7.58	−16.64	−13.98	−16.65	−23.19	−19.28
Agricultural good price	49.77	187.83	132.36	185.14	609.68	270.02
MAD of acreage shares	69.65	63.84	64.22	63.81	63.36	64.51
MAD of between-country acreage shares	52.33	41.75	42.73	41.73	40.65	41.78
MAD of international trade volumes		104.30	119.02	103.34	62.29	73.54
MAD of import trade shares		69.00	91.60	68.67	0.00	53.10

The results for the integrated world market only for the non-agricultural good are very close to the benchmark results. Only Sub-Saharan Africa presents significantly different, and lower, losses under this modeling. Sub-Saharan African countries are, indeed, the countries where non-agricultural terms-of-trade effects are the highest in table 4. Except for these countries, the effects are small. This result comes as a confirmation of the welfare decomposition of table 4. The combination of the assumptions of a quasi-linear utility function with an integrated world market for the non-agricultural good implies that this model is *de facto* a partial equilibrium model. This result validates the partial equilibrium approach focused on the agricultural sector adopted in several studies (e.g., Havlík et al., 2014; Hertel et al., 2014) including *de facto* CDS, with the caveat that it may underestimate the welfare losses in some poor countries. The similarity between the partial equilibrium and the general equilibrium results are also related to the fact that the demand system rules out income effects on agricultural good demand, which are likely to be low in developed countries but may not be in poor countries. Additionally, the presence of large inter-sectoral distortions (Adamopoulos et al., 2017) or complex general equilibrium effects may also qualify this conclusion, but that remains to be demonstrated.

The simulation with Caliendo and Parro's estimated trade elasticity is reported in column 3. It reduces by one-fourth the global welfare losses and the agricultural prices increase. Trade reallocation increases. But the Armington assumption for trade does not put any constraint per se on the trade volumes; it defines how import expenditures are shared between exporters. Correspondingly, we report in the last row the mean absolute deviation of the changes in trade shares expressed as $\sum_{i,j\in\mathcal{I},i\neq j,k\in\mathcal{K}^c} X_{ji}^k|\hat{X}_{ji}^k/\hat{X}_j^k - 1|/\sum_{i,j\in\mathcal{I},i\neq j,k\in\mathcal{K}^c} X_{ji}^k$. In the benchmark, the mean absolute change in the import shares is 69%. It increases a lot to 92% with the increased elasticity.

Column 5 presents the results with bilateral import shares fixed at their initial levels. Since imports of various origins are considered as less substitutable, countries are obliged to rely more on their baseline trade patterns, so they experience much larger price increases than in the benchmark and larger decreases in the consumption of the agricultural good bundle. In this case, world welfare changes amount to −3.45%, almost twice as the benchmark value. This increase in losses is comparable to the increase obtained when restricting acreage changes in table 8. Despite the strong restriction on trade, the mean absolute deviations of international trade volumes are large, 62%, showing there are still a lot of trade adjustments taking place even if the import shares have been fixed.

The counterfactual exercise proposed by CDS is presented in column 6. If export shares are fixed, global welfare losses increase by one-fourth, much more than in CDS where the increase in losses does not exceed 4%. From the mean absolute deviations of trade volumes and import shares in the last two rows, it is also clear that this restriction on trade reallocations is not very strong. A lot of trade changes can still take place. So, to avoid a downward bias when judging the role of international trade in climate change adaptation, we prefer to use the exercise reported in column 5.

7 Conclusion

This paper estimates how climate change in the agricultural sector will affect the world economy, focusing on the influence on trade and welfare of the assumptions about the various adjustments margins. Using an Armington quantitative trade model with spatially explicit land uses that builds on Costinot et al. (2016), we simulate a counterfactual scenario of climate change where the shock on crop yields at the horizon 2080 is based on crop science. In our benchmark calibration, climate change reduces welfare globally by 1.76%, with a lot of heterogeneity as net-food-importing tropical countries lose from the negative productivity shocks and increased global food prices, while countries exporting agricultural products tend to gain thanks to improved terms of trade.

These welfare changes are the results of demand-side, supply-side, and trade adjustments that all contribute to mitigate the adverse shock. Supply-side adjustments are crucial by allowing production to relocate where it is more profitable. In particular, the most important supply-side adaptation appears to be the ability to introduce on a field crops that were not productive before climate change, a feature made possible by the functional forms used in our spatially explicit modeling. While crucial, the supply-side adjustments could not prevent large welfare losses if international trade could not play its adjustment role. Demand for agricultural products is quite inelastic given their irreplaceable role, and large supply-side adjustments are not enough to ensure that domestic supply will match domestic demand either in terms of overall food quantity or in terms of the food basket composition. Global welfare impacts could be almost doubled when assuming constant import shares, or reduced by two-thirds when assuming fully integrated world markets.

Adaptation to climate change in agriculture is often synonymous with investments in irrigation infrastructure, development of new crop varieties, or as confirmed by our paper, adapting the crop mix to the new climate, which are indisputably important supply-side adjustments. But this paper demonstrates that these adjustments will not prevent the creation of large imbalances in domestic markets that can only be resolved by large reallocations in international trade. These reallocations may not happen as smoothly as in our stylized model. Allowing a completely different pattern of trade to emerge involves large investments in transport infrastructures that will have to be planned years in advance. In addition, agriculture is the sector with the highest prevalence of distortionary public interventions, a fact that is neglected in the model. The domestic political economy at stake, not today, but in the next 70 years, is clearly beyond the scope of our analysis. Changing demographic and political weights will impact which groups will be favored by public policies, in particular regarding price distortions. By altering incentives, these policies have the potential to put agricultural systems into maladaptative pathways by locking-in specializations that no longer make sense. Our results have also serious implications regarding the governance of the global trading system. Indeed, we find major welfare redistribution effects driven by changes in terms of trade. Historically, multilateral and regional trade agreements have been driven by the need of addressing terms-of-trade effects originated by non-cooperative policies. Therefore, without the proper policies in place to address the roots of the issue (climate change agreement) and the resilience of existing trading institutions (WTO), the pressure to use trade policies instrument to mitigate the terms of trade impact of agricultural productivity shock may exacerbate the initial efficiency shock.

Given the model parsimony, some margins of adaptation have been neglected, such as irrigation or deforestation, which could constitute interesting developments of the land-use theory sketched here. While these margins could contribute to reduce the welfare losses, they are unlikely to significantly change the role of international trade. On the contrary, this paper may understate the true benefits of international trade in climate change adaptation. The adopted Armington assumption, while common in international trade theory, presents the drawback shared with many modern trade theories (except for Helpman et al., 2008) of neglecting the extensive margin associated with new trading partners. The climate change shocks affect comparative advantages so much that trade patterns in agricultural products may be radically different. But, because of its limits, the Armington assumption may prevent the emergence of trade patterns structurally too different. This problem raises the challenges of the development of a new trade theory compatible with observed bilateral trade flows, perfect competition, and zero trade flows across pairs of countries.

Appendix

A Proof of existence and uniqueness of land rents per unit of production

To prove that equation (50) has a unique solution, let define $\rho_i^k = -\theta \ln r_i^k$ and rewrite the equation in log:

$$\rho_i^k = \ln\left\{\left(R_i^k\right)^{-1}\sum_{f\in\mathcal{F}_i} s_i^f \left(A_i^{fk}\right)^\theta \left[\sum_{l\in\mathcal{K}_c} \mathrm{e}^{-\rho_i^l}\left(A_i^{fl}\right)^\theta\right]^{(1-\theta)/\theta}\right\} = h_i^k\left(\rho_i\right), \tag{A1}$$

where ρ_i is the vector of ρ_i^k, $k \in \mathcal{K}^c$ and $R_i^k > 0$.

We define the mapping $h_i : \mathbb{R}^{n_i} \to \mathbb{R}^{n_i}$, where n_i is the number of crops grown in country i (i.e., the crops for which $R_i^k > 0$). Now, we calculate the elements of the Jacobian of h_i:

$$\frac{\partial h_i^k\left(\rho_i\right)}{\partial \rho_i^l} = \frac{\theta-1}{\theta}\left(\frac{1}{\exp h_i^k\left(\rho_i\right)}\right)\left(R_i^k\right)^{-1}\sum_{f\in\mathcal{F}_i} s_i^f\left(A_i^{fk}\right)^\theta \mathrm{e}^{-\rho_i^l}\left(A_i^{fl}\right)^\theta\left[\sum_{l'\in\mathcal{K}_c}\mathrm{e}^{-\rho_i^{l'}}\left(A_i^{fl'}\right)^\theta\right]^{1/\theta-2}, \tag{A2}$$

$$= \frac{\theta-1}{\theta}\left(\frac{1}{\exp h_i^k\left(\rho_i\right)}\right)\left(R_i^k\right)^{-1}\sum_{f\in\mathcal{F}_i} s_i^f\left(A_i^{fk}\right)^\theta \pi_i^{fl}\left[\sum_{l'\in\mathcal{K}_c}\mathrm{e}^{-\rho_i^{l'}}\left(A_i^{fl'}\right)^\theta\right]^{(1-\theta)/\theta}. \tag{A3}$$

According to the mean value theorem, for any $\rho_{i,0}$ and $\rho_{i,1} \in \mathbb{R}^{n_i}$ there exists some $t_i \in [0,1]$ such that $\tilde{\rho}_i = t_i\rho_{i,0} + (1-t_i)\rho_{i,1}$ satisfies

$$h_i^k\left(\rho_{i,1}\right) - h_i^k\left(\rho_{i,0}\right) = \sum_{l\in\mathcal{K}^c}\frac{\partial h_i^k\left(\tilde{\rho}_i\right)}{\partial\tilde{\rho}_i^l}\left(\rho_{i,1}^l - \rho_{i,0}^l\right). \tag{A4}$$

Under the sup norm, $\|\rho\| = \max_k\left|\rho^k\right|$, we have

$$\left\|h_i\left(\rho_{i,1}\right) - h_i\left(\rho_{i,0}\right)\right\| \leq \left\|\rho_{i,1}-\rho_{i,0}\right\|\sum_{l\in\mathcal{K}^c}\frac{\partial h_i^k\left(\tilde{\rho}_i\right)}{\partial\tilde{\rho}_i^l}. \tag{A5}$$

Using that $\sum_{l\in\mathcal{K}^c}\pi_i^{fl} = 1$, we have

$$\sum_{l\in\mathcal{K}^c}\frac{\partial h_i^k\left(\tilde{\rho}_i\right)}{\partial\tilde{\rho}_i^l} = \frac{\theta-1}{\theta} < 1, \tag{A6}$$

so h_i is a contraction mapping and the contraction mapping theorem implies the existence of a unique fixed point ρ_i for h_i and a unique solution to equation (50). □

B Effects of a crop productivity shifter

We aim here to prove that adjusting the GAEZ potential yields by a constant country-crop productivity shifter does not alter the results. For this, we assume now that in a parcel yields are distributed Fréchet with shape θ and scale $\gamma\delta_i^k A_i^{fk}$, where δ_i^k is a country- and product-specific productivity shifter. This change leads to the following new equations replacing equations (22) and (26):

$$\pi_i^{fk} = \frac{\left(r_i^k \delta_i^k A_i^{fk}\right)^\theta}{\sum_{l\in\mathcal{K}^c, r_i^l \geq 0} \left(r_i^l \delta_i^l A_i^{fl}\right)^\theta}, \tag{A7}$$

$$Q_i^k = \delta_i^k \sum_{f\in\mathcal{F}_i} s_i^f A_i^{fk} \left(\pi_i^{fk}\right)^{(\theta-1)/\theta}, \tag{A8}$$

and to a slightly different calibration for the land rents, where equation (50) is replaced by

$$\left(\delta_i^k r_i^k\right)^{-\theta} = \left(R_i^k\right)^{-1} \sum_{f\in\mathcal{F}_i} s_i^f \left(A_i^{fk}\right)^\theta \left[\sum_{l\in\mathcal{K}_c} \left(\delta_i^l r_i^l A_i^{fl}\right)^\theta\right]^{(1-\theta)/\theta}, \tag{A9}$$

which defines a contraction mapping in $\delta_i^k r_i^k$.

Values for $\delta_i^k r_i^k$ consistent with (A9) lead to unique benchmark values for π_i^{fk} and Q_i^k/δ_i^k. If the productivity shifters δ_i^k are not changed in counterfactual simulations, the values of δ_i^k do not affect the results, because the relative changes of production are now given by

$$\hat{Q}_i^k = \sum_{f\in\mathcal{F}_i} \frac{\delta_i^k}{Q_i^k} s_i^f A_i^{fk\prime} \frac{\left(\delta_i^k r_i^k \hat{r}_i^k A_i^{fk\prime}\right)^{\theta-1}}{\left[\sum_{l\in\mathcal{K}^c} \left(\delta_i^l r_i^l \hat{r}_i^l A_i^{fl\prime}\right)^\theta\right]^{(\theta-1)/\theta}}. \tag{A10}$$

Without incidences on the results, δ_i^k could be calibrated so that Q_i^k replicate the physical production values in tons in FAOSTAT.

C Welfare

C.1 Welfare in a corner solution

Expenditure function For a corner solution, expenditure and utility are limited to the food bundle:

$$E_i = P_i C_i, \tag{A11}$$

and

$$U_i = \beta_i^{1/\epsilon} \begin{cases} C_i^{1-1/\epsilon}/(1-1/\epsilon) & \text{if } \epsilon \neq 1, \\ \ln C_i & \text{if } \epsilon = 1. \end{cases} \tag{A12}$$

Combining equations (A11) and (A12) gives the expenditure function (52).

Equivalent variation To find the expression of the equivalent variation, we first need to express the counterfactual utility as much as possible in terms of relative changes:

$$U_i' = C_i^0 \hat{C}_i^0 + \beta_i^{1/\epsilon} \begin{cases} \left(C_i \hat{C}_i\right)^{1-1/\epsilon}/(1-1/\epsilon) & \text{if } \epsilon \neq 1, \\ \ln\left(C_i \hat{C}_i\right) & \text{if } \epsilon = 1. \end{cases} \tag{A13}$$

Noting that $\beta_i = C_i \left(P_i/P_i^0\right)^{\epsilon}$, we have

$$P_i^0 U_i' = P_i^0 C_i^0 \hat{C}_i^0 + P_i C_i \begin{cases} \hat{C}_i^{1-1/\epsilon}/(1-1/\epsilon) & \text{if } \epsilon \neq 1, \\ \left[\ln\left(P_i C_i \hat{C}_i\right) - \ln P_i\right] & \text{if } \epsilon = 1. \end{cases} \tag{A14}$$

Then substituting the counterfactualy utility in equation (A14) in the expenditure function gives the equivalent variation in (54).

Thresholds From equation (9), a corner solution occurs if $E_i < \beta_i P_i^{1-\epsilon} \left(P_i^0\right)^{\epsilon}$. Using the expression of the expenditure function in (51), it gives

$$\beta_i P_i^{1-\epsilon} \left(P_i^0\right)^{\epsilon} > P_i^0 U_i + \beta_i \left(P_i^0\right)^{\epsilon} \begin{cases} P_i^{1-\epsilon}/(1-\epsilon) & \text{if } \epsilon \neq 1, \\ \left[1 - \ln\left(\beta_i P_i^0/P_i\right)\right] & \text{if } \epsilon = 1, \end{cases} \tag{A15}$$

and so

$$\begin{cases} U_i < \left[\beta_i/(1-1/\epsilon)\right] \left(P_i/P_i^0\right)^{1-\epsilon} & \text{if } \epsilon \neq 1, \\ U_i < \beta_i \ln\left(\beta_i P_i^0/P_i\right) & \text{if } \epsilon = 1. \end{cases} \tag{A16}$$

Now using $\beta_i = C_i \left(P_i/P_i^0\right)^{\epsilon}$ and replacing utility by its expression in equation (A14) gives the thresholds in equation (55).

C.2 Welfare decomposition

From the definition of the equivalent variation and equation (51), we have:

$$\mathrm{d}\, EV_i = \frac{\partial e\left(P_i^0, P_i, U_i\right)}{\partial U_i} \mathrm{d}\, U_i = P_i^0 U_i \, \mathrm{d} \ln U_i. \tag{A17}$$

Then from the definition of the expenditure function and Shephard's lemma:

$$\begin{aligned} \mathrm{d}\, E_i &= \frac{\partial e\left(P_i^0, P_i, U_i\right)}{\partial P_i^0} \mathrm{d}\, P_i^0 + \frac{\partial e\left(P_i^0, P_i, U_i\right)}{\partial P_i} \mathrm{d}\, P_i + \frac{\partial e\left(P_i^0, P_i, U_i\right)}{\partial U_i} \mathrm{d}\, U_i, && \text{(A18)} \\ &= C_i^0 \, \mathrm{d}\, P_i^0 + C_i \, \mathrm{d}\, P_i + \mathrm{d}\, EV_i, && \text{(A19)} \end{aligned}$$

and so

$$\mathrm{d}\, EV_i = E_i \, \mathrm{d} \ln E_i - P_i^0 C_i^0 \, \mathrm{d} \ln P_i^0 - P_i C_i \, \mathrm{d} \ln P_i. \tag{A20}$$

From now on, we assume no trade deficits, so from equation (35):

$$E_i \, \mathrm{d} \ln E_i = w_i N_i \, \mathrm{d} \ln w_i + \sum_{k \in \mathcal{K}^c} R_i^k \, \mathrm{d} \ln R_i^k. \tag{A21}$$

Land rents can be further decomposed using equation (27), for $k \in \mathcal{K}^c$:

$$\mathrm{d} \ln R_i^k = \mathrm{d} \ln r_i^k + \mathrm{d} \ln Q_i^k. \tag{A22}$$

From equations (22) and (26) and using that $\mathrm{d} \ln A_i^{fk}(\omega) = \mathrm{d} \ln A_i^{fk}$, we get for $\mathrm{d} \ln Q_i^k$:

$$\mathrm{d} \ln Q_i^k = \sum_{f \in \mathcal{K}_i} \frac{Q_i^{fk}}{Q_i^k} \left[\mathrm{d} \ln A_i^{fk} + (\theta - 1)\left(\mathrm{d} \ln r_i^k + \mathrm{d} \ln A_i^{fk}\right) - \sum_{l \in \mathcal{K}^c} (\theta - 1) \pi_i^{fl} \left(\mathrm{d} \ln r_i^l + \mathrm{d} \ln A_i^{fl}\right) \right]. \tag{A23}$$

Now we can sum $R_i^k \,\mathrm{d}\ln R_i^k$ over k:

$$\sum_{k\in\mathcal{K}^c} R_i^k \,\mathrm{d}\ln R_i^k = \sum_{f\in\mathcal{F}_i, k\in\mathcal{K}^c} r_i^k Q_i^{fk} \left[\theta\left(\mathrm{d}\ln r_i^k + \mathrm{d}\ln A_i^{fk}\right) - \sum_{l\in\mathcal{K}^c} (\theta-1)\,\pi_i^{fl}\left(\mathrm{d}\ln r_i^l + \mathrm{d}\ln A_i^{fl}\right)\right],$$
$$= \sum_{f\in\mathcal{F}_i, k\in\mathcal{K}^c} \left(\mathrm{d}\ln r_i^k + \mathrm{d}\ln A_i^{fk}\right)\left[\theta r_i^k Q_i^{fk} - (\theta-1)\,\pi_i^{fk} \sum_{l\in\mathcal{K}^c} r_i^l Q_i^{fl}\right]. \tag{A24}$$

Combining equations (22) and (26), we obtain $\pi_i^{fk} = r_i^k Q_i^{fk} / \sum_{l\in\mathcal{K}^c} r_i^l Q_i^{fl}$, which allows us to simplify equation (A24) in

$$\sum_{k\in\mathcal{K}^c} R_i^k \,\mathrm{d}\ln R_i^k = \sum_{f\in\mathcal{F}_i, k\in\mathcal{K}^c} r_i^k Q_i^{fk}\left(\mathrm{d}\ln r_i^k + \mathrm{d}\ln A_i^{fk}\right). \tag{A25}$$

Now from labor market clearing we have:

$$w_i N_i = \sum_{k\in\mathcal{K}} w_i N_i^k = \sum_{k\in\mathcal{K}} \phi_i^{k,\text{labor}}\left(\sum_{j\in\mathcal{I}} X_{ij}^k\right). \tag{A26}$$

Multiplying equation (A26) by $\mathrm{d}\ln w_i$ and using (36), we get

$$w_i N_i \,\mathrm{d}\ln w_i = \sum_{k\in\mathcal{K}}\left(\sum_{j\in\mathcal{I}} X_{ij}^k\right)\left(\mathrm{d}\ln p_i^k - \phi_i^{k,\text{land}}\,\mathrm{d}\ln r_i^k - \phi_i^{k,\text{feed}}\,\mathrm{d}\ln P_i^{k,\text{feed}}\right). \tag{A27}$$

Then, we can decompose final consumption:

$$P_i^0 C_i^0 \,\mathrm{d}\ln P_i^0 + P_i C_i \,\mathrm{d}\ln P_i = P_i^0 C_i^0\left(\sum_{j\in\mathcal{I}} \alpha_{ji}^0 \,\mathrm{d}\ln p_j^0\right) + P_i C_i\left(\sum_{k\in\mathcal{K}^a, j\in\mathcal{I}} \alpha_i^k \alpha_{ji}^k \,\mathrm{d}\ln p_j^k\right),$$
$$= \sum_{j\in\mathcal{I}} X_{ji}^0 \,\mathrm{d}\ln p_j^0 + \sum_{k\in\mathcal{K}^a, j\in\mathcal{I}} \left(X_i^k - P_i^k x_i^k\right)\alpha_{ji}^k \,\mathrm{d}\ln p_j^k. \tag{A28}$$

Finally, from equation (A20), we combine equations (A25), (A27), and (A28). Terms in $\mathrm{d}\ln r_i^k$ and terms related to feed demand ($\mathrm{d}\ln P_i^{k,\text{feed}}$ and $P_i^k x_i^k$) cancel, and we get equation (56).

D Crop aggregation

We show here under which conditions and how crops can be aggregated together. Let define a set $\mathcal{K}^\kappa \subset \mathcal{K}^c$ of crops to be aggregated. We refer to the aggregate crop by $k = \kappa$ and to the new set of crops that include the aggregate crop but no longer the crops that have been aggregated by $\tilde{\mathcal{K}}^c$.

Given equation (22), for the aggregate crop to use the same share of land in each field as the sum of the individual crops, we need

$$\sum_{k\in\mathcal{K}^\kappa} \frac{\left(r_i^k A_i^{fk}\right)^\theta}{\sum_{l\in\mathcal{K}^c}\left(r_i^l A_i^{fl}\right)^\theta} = \frac{\left(r_i^\kappa A_i^{f\kappa}\right)^\theta}{\sum_{l\in\tilde{\mathcal{K}}^c}\left(r_i^l A_i^{fl}\right)^\theta}, \tag{A29}$$

where r_i^κ and $A_i^{f\kappa}$ are the land rent and potential yield of the crop aggregate and need to be determined. The crop aggregation should not affect the expected return from a field, so

$$\sum_{l\in\mathcal{K}^c}\left(r_i^l A_i^{fl}\right)^{\theta}=\sum_{l\in\tilde{\mathcal{K}}^c}\left(r_i^l A_i^{fl}\right)^{\theta}, \tag{A30}$$

which together with equation (A29) implies

$$\sum_{k\in\mathcal{K}^\kappa}\left(r_i^k A_i^{fk}\right)^{\theta}=\left(r_i^\kappa A_i^{f\kappa}\right)^{\theta}, \tag{A31}$$

which defines the aggregate potential yield given the aggregate land rent:

$$A_i^{f\kappa}=\frac{\left[\sum_{k\in\mathcal{K}^\kappa}\left(r_i^k A_i^{fk}\right)^{\theta}\right]^{1/\theta}}{r_i^\kappa}. \tag{A32}$$

The equality of field-level production implies from (25)

$$\sum_{k\in\mathcal{K}^\kappa}A_i^{fk}\left(r_i^k A_i^{fk}\right)^{\theta-1}=A_i^{f\kappa}\left(r_i^\kappa A_i^{f\kappa}\right)^{\theta-1}, \tag{A33}$$

Equations (A32) and (A33) can hold together only if $r_i^\kappa=r_i^k$ for all $k\in\mathcal{K}^\kappa$, which implies the following expression for the aggregate potential yield

$$A_i^{f\kappa}=\left[\sum_{k\in\mathcal{K}^\kappa}\left(A_i^{fk}\right)^{\theta}\right]^{1/\theta}. \tag{A34}$$

E Elastic yields

We now assume that yields are elastic through a simple isoelastic specification:

$$Q_i^{fk}(\omega)=\min\left[A_i^{fk}(\omega)\left(I_i^{fk}(\omega)/\bar{I}_i^{fk}\right)^{\eta},N_i^{fk}(\omega)/\nu_i^k\right], \tag{A35}$$

where $I_i^{fk}(\omega)$ is the level of (fertilizer) inputs of the non-agricultural good and $0\leq\eta<1-1/\theta$ is the elasticity of crop output to the input of the non-agricultural good. The upper bound on η is necessary to ensure that the Fréchet-distributed land rents have finite mean.

From the Leontief structure, if the parcel ω is planted with $k\in\mathcal{K}^c$, we have

$$Q_i^{fk}(\omega)=A_i^{fk}(\omega)\left(I_i^{fk}(\omega)/\bar{I}_i^{fk}\right)^{\eta}=N_i^{fk}(\omega)/\nu_i^k. \tag{A36}$$

We can express the parcel land rent for a planted crop, $R_i^{fk}(\omega)$, as the residual of crop revenue after subtracting labor costs and non-agricultural input costs:

$$R_i^{fk}(\omega)=p_i^k Q_i^{fk}(\omega)-w_i N_i^{fk}(\omega)-P_i^0 I_i^{fk}(\omega). \tag{A37}$$

Maximization of land rents with respect to non-agricultural inputs gives

$$I_i^{fk}(\omega)=\eta\frac{p_i^k-w_i\nu_i^k}{P_i^0}Q_i^{fk}(\omega). \tag{A38}$$

Substituting $I_i^{fk}(\omega)$ by $\bar{I}_i^{fk}\left(Q_i^{fk}(\omega)/A_i^{fk}(\omega)\right)^{1/\eta}$ leads to an expression of $Q_i^{fk}(\omega)$ as a function of prices only:

$$Q_i^{fk}(\omega) = \left(A_i^{fk}(\omega)\right)^{1/(1-\eta)}\left(\eta\frac{p_i^k - w_i\nu_i^k}{\bar{I}_i^{fk}P_i^0}\right)^{\eta/(1-\eta)}, \tag{A39}$$

from which we can derive the land rents:

$$R_i^{fk}(\omega) = \left(r_i^k A_i^{fk}(\omega)\right)^{1/(1-\eta)}\left(\bar{I}_i^{fk}P_i^0\right)^{\eta/(\eta-1)}(1-\eta)\,\eta^{\eta/(1-\eta)}. \tag{A40}$$

From the properties of the Fréchet distribution, it follows that $R_i^{fk}(\omega)$ is distributed Fréchet with parameters $(1-\eta)\theta$ and $\gamma\left(r_i^k A_i^{fk}\right)^{1/(1-\eta)}\left(\bar{I}_i^{fk}P_i^0\right)^{\eta/(\eta-1)}(1-\eta)\,\eta^{\eta/(1-\eta)}$. The probability that the crop k is the most profitable crop on the parcel ω is given

$$\pi_i^{fk} = \frac{\left[r_i^k A_i^{fk}\left(\bar{I}_i^{fk}\right)^{-\eta}\right]^\theta}{\sum_{l\in\mathcal{K}^c, r_i^l\geq 0}\left[r_i^l A_i^{fl}\left(\bar{I}_i^{fl}\right)^{-\eta}\right]^\theta}. \tag{A41}$$

The production at the field level is given by

$$Q_i^{fk} = s_i^f\pi_i^{fk}\,\mathrm{E}\left[A_i^{fk}(\omega)\left(I_i^{fk}(\omega)/\bar{I}_i^{fk}\right)^\eta |R_i^{fk}(\omega)\in\arg\max_{l\in\mathcal{K}^c}R_i^{fl}(\omega)\right], \tag{A42}$$

$$= s_i^f\pi_i^{fk}\left(\frac{\eta r_i^k}{\bar{I}_i^{fk}P_i^0}\right)^{\eta/(1-\eta)}\mathrm{E}\left[\left(A_i^{fk}(\omega)\right)^{1/(1-\eta)}|R_i^{fk}(\omega)\in\arg\max_{l\in\mathcal{K}^c}R_i^{fl}(\omega)\right]. \tag{A43}$$

From the standard properties of the Fréchet distribution we have

$$E\left[R_i^{fk}(\omega)\,|R_i^{fk}(\omega)\in\arg\max_{l\in\mathcal{K}^c}R_i^{fl}(\omega)\right] = \frac{\Gamma(1-1/(1-\eta)\theta)}{\Gamma(1-1/\theta)}\left(\eta P_i^0\right)^{\eta/(\eta-1)}(1-\eta)\left\{\sum_{l\in\mathcal{K}^c, r_i^l\geq 0}\left[r_i^l A_i^{fl}\left(\bar{I}_i^{fk}\right)^{-\eta}\right]^\theta\right\}^{1/(1-\eta)\theta}. \tag{A44}$$

So

$$E\left[\left(A_i^{fk}(\omega)\right)^{1/(1-\eta)}|R_i^{fk}(\omega)\in\arg\max_{l\in\mathcal{K}^c}R_i^{fl}(\omega)\right] = \frac{\Gamma(1-1/(1-\eta)\theta)}{\Gamma(1-1/\theta)}\left(A_i^{fk}\right)^{1/(1-\eta)}\left(\pi_i^{fk}\right)^{-1/(1-\eta)\theta}, \tag{A45}$$

and

$$Q_i^{fk} = s_i^f\left(\frac{\eta r_i^k}{\bar{I}_i^{fk}P_i^0}\right)^{\eta/(1-\eta)}\frac{\Gamma(1-1/(1-\eta)\theta)}{\Gamma(1-1/\theta)}\left(A_i^{fk}\right)^{1/(1-\eta)}\left(\pi_i^{fk}\right)^{1-1/(1-\eta)\theta}. \tag{A46}$$

From (A46), the elasticity of production to output price is

$$\frac{\partial\ln Q_i^k}{\partial\ln p_i^k} = \frac{p_i^k}{r_i^k}\Bigg[\underbrace{\frac{\eta}{1-\eta}}_{\text{Yield}} + \underbrace{\frac{\theta(1-\eta)-1}{1-\eta}\sum_{f\in\mathcal{F}_i}\left(1-\pi_i^{fk}\right)\frac{Q_i^{fk}}{Q_i^k}}_{\text{Acreage}}\Bigg]. \tag{A47}$$

It is the sum of a yield and an acreage elasticity. Since $[\theta(1-\eta)-1]/(1-\eta)\leq\theta-1$, for the same θ, the acreage elasticity is reduced in presence of elastic yields compared to equation (29). For $\pi_i^{fk}\approx 0$, the total elasticity is

$(\theta - 1)\, p_i^k / r_i^k$, the same elasticity as the model with inelastic yields. However, for $\pi_i^{fk} \approx 1$, the total elasticity corresponds to the yield elasticity and is $\left(p_i^k / r_i^k\right) \eta / (1-\eta) \geq 0$ while it is zero in the absence of a yield response. If $\sum_{f \in \mathcal{F}_i} \left(1 - \pi_i^{fk}\right) Q_i^{fk} / Q_i^k$ is not dependent of the calibration (which is not the case but the differences are too small to matter), to maintain the same acreage elasticity when yields are elastic, one should adjust the degree of within-field heterogeneity so that $\tilde{\theta} = \theta + \eta/(1-\eta)$. One limit of this approach is that because of its simplicity, all crops react similarly to input levels, even grass.

From the above, the demand for each input and the field-level land rents can be derived:

$$N_i^{fk} = \nu_i^k Q_i^{fk}, \tag{A48}$$

$$I_i^{fk} = \eta \frac{r_i^k}{P_i^0} Q_i^{fk}, \tag{A49}$$

$$R_i^{fk} = (1-\eta)\, r_i^k Q_i^{fk}. \tag{A50}$$

Using that $\lim_{n \to 0} n^{n/(1-n)} = 1$, it is easy to verify that with $\eta = 0$ all the equations in this appendix are the same as those of the benchmark model and the model with elastic yields nests the benchmark model.

In exact hat algebra, equations (36), (37), and (45) are now replaced by

$$\hat{p}_i^k = \phi_i^{k,\text{labor}} \hat{w}_i + \left(\phi_i^{k,\text{land}} + \phi_i^{k,\text{inputs}}\right) \hat{r}_i^k + \phi_i^{k,\text{feed}} \hat{P}_i^{k,\text{feed}}, \tag{A51}$$

$$\hat{Q}_i^k = \left(\eta \frac{r_i^k \hat{r}_i^k}{\bar{I}_i^{fk} P_i^0 \hat{P}_i^0}\right)^{\eta/(1-\eta)} \frac{\Gamma\left(1 - 1/(1-\eta)\,\theta\right)}{\Gamma\left(1 - 1/\theta\right)} \sum_{f \in \mathcal{F}_i} \frac{s_i^f \left(A_i^{fk\prime}\right)^{1/(1-\eta)}}{Q_i^k} \left\{ \frac{\left[r_i^k \hat{r}_i^k A_i^{fk\prime} \left(\bar{I}_i^{fk}\right)^{-\eta}\right]^\theta}{\sum_{l \in \mathcal{K}^c} \left[r_i^l \hat{r}_i^l A_i^{fl\prime} \left(\bar{I}_i^{fl}\right)^{-\eta}\right]^\theta} \right\}^{1 - 1/(1-\eta)\theta}, \tag{A52}$$

$$X_i^k \hat{X}_i^k = P_i^k C_i^k \hat{P}_i^k \hat{C}_i^k + \mathbf{1}_{k=0} \left(\sum_{l \in \mathcal{K}^c} P_i^0 I_i^l \hat{P}_i^0 \hat{I}_i^l \right) + \mathbf{1}_{k \in \mathcal{K}^c} \left(+ P_i^k x_i^k \hat{P}_i^k \hat{x}_i^k \right), \tag{A53}$$

and the aggregate demand for inputs is given by

$$\hat{I}_i^k = \left(\hat{r}_i^k / \hat{P}_i^0\right) \hat{Q}_i^k. \tag{A54}$$

For the calibration, in the absence of any information on inputs level in the GAEZ database that we could have used in calibration, we assume that inputs are the same for all fields for a given country-crop couple: $\bar{I}_i^k = \bar{I}_i^{fk}$. Then, by combining equations (A46) and (A50), one gets

$$\left[\frac{r_i^k \left(\bar{I}_i^k\right)^{-\eta}}{P_i^0}\right]^{-\theta} = P_i^0 \left(R_i^k\right)^{-1} (1-\eta)\, \eta^{\eta/(1-\eta)} \frac{\Gamma\left(1 - 1/(1-\eta)\,\theta\right)}{\Gamma\left(1 - 1/\theta\right)} \sum_{f \in \mathcal{F}_i} s_i^f \left(A_i^{fk}\right)^\theta \left\{ \sum_{l \in \mathcal{K}^c} \left[\frac{r_i^l \left(\bar{I}_i^l\right)^{-\eta}}{P_i^0} A_i^{fl}\right]^\theta \right\}^{1/(1-\eta)\theta - 1}. \tag{A55}$$

So for given P_i^0, $r_i^k \left(\bar{I}_i^k\right)^{-\eta} / P_i^0$ can be found by fixed-point iteration. Since π_i^{fk} can also be expressed as a function of $r_i^k \left(\bar{I}_i^k\right)^{-\eta} / P_i^0$:

$$\pi_i^{fk} = \frac{\left\{\left[r_i^k \left(\bar{I}_i^k\right)^{-\eta} / P_i^0\right] A_i^{fk}\right\}^\theta}{\sum_{l \in \mathcal{K}^c, r_i^l \geq 0} \left\{\left[r_i^l \left(\bar{I}_i^l\right)^{-\eta} / P_i^0\right] A_i^{fl}\right\}^\theta}, \tag{A56}$$

the values assumed for P_i^0 have no effect on π_i^{fk}. However, in equation (A52), $\hat{Q}_i^k$ depends apparently on r_i^k, P_i^0, and $\bar{I}_i^k$. In reality, the only effect of these initial values is to scale the initial values of Q_i^{fk} and so of Q_i^k, but they have no counterfactual influence.

To calibrate the model with elastic yields, one needs η which in addition of determining the yield elasticity is also equal from equation (A49) to the budget share of the non-agricultural input in crop revenues less labor cost. When calibrating the model with elastic yield, we increase θ to maintain the acreage elasticity constant. Another issue is from where to allocate the initial input costs. For crops other than grass, the input costs are taken from the labor share. For grass, it is taken from land.

F Supplementary tables

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

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

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

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

References

Adamopoulos, T., L. Brandt, J. Leight, and D. Restuccia (2017). *Misallocation, Selection and Productivity: A Quantitative Analysis with Panel Data from China*. Working Paper 23039. National Bureau of Economic Research.

Aguiar, A., B. Narayanan, and R. McDougall (2016). “An Overview of the GTAP 9 Data Base”. *Journal of Global Economic Analysis*, 1(1), pp. 181–208.

Ahammad, H., E. Heyhoe, G. Nelson, R. Sands, S. Fujimori, T. Hasegawa, D. van der Mensbrugghe, E. Blanc, P. Havlík, H. Valin, P. Kyle, D. M. d’Croz, H. van Meijl, C. Schmitz, H. Lotze-Campen, M. von Lampe, and A. Tabeau (2015). “The role of international trade under a changing climate: Insights from global economic modelling”. In: *Climate Change and Food Systems: Global Assessments and Implications for Food Security and Trade*. Ed. by A. Elbehri. Rome: FAO. Chap. 10, pp. 292–312.

Alexandratos, N. and J. Bruinsma (2012). *World Agriculture Towards 2030/2050: The 2012 Revision*. Rome: Food and Agriculture Organization of the United Nations.

Anderson, J. E. and E. van Wincoop (2003). “Gravity with Gravitas: A Solution to the Border Puzzle”. *The American Economic Review*, 93(1), pp. 170–192.

Anderson, K., G. C. Rausser, and J. F. Swinnen (2013). “Political Economy of Public Policies: Insights from Distortions to Agricultural and Food Markets”. *Journal of Economic Literature*, 51(2), pp. 423–477.

Andreyeva, T., M. W. Long, and K. D. Brownell (2010). “The Impact of Food Prices on Consumption: A Systematic Review of Research on the Price Elasticity of Demand for Food”. *American Journal of Public Health*, 100(2), pp. 216–222.

Atkin, D. (2013). “Trade, Tastes, and Nutrition in India”. *American Economic Review*, 103(5), pp. 1629–1663.

— (2016). “The Caloric Costs of Culture: Evidence from Indian Migrants”. *American Economic Review*, 106(4), pp. 1144–1181.

Beckman, J., R. Keeney, and W. Tyner (2011). “Feed demands and coproduct substitution in the biofuel era”. *Agribusiness*, 27(1), pp. 1–18.

Berry, S. T. (2011). *Biofuels Policy and the Empirical Inputs to GTAP Models*. Report. California Air Resources Board.

Berry, S. T. and W. Schlenker (2011). *Empirical evidence on crop elasticities*. Report. International Council on clean Transportation.

Caliendo, L. and F. Parro (2015). “Estimates of the Trade and Welfare Effects of NAFTA”. *The Review of Economic Studies*, 82(1), pp. 1–44.

Carpentier, A. and E. Letort (2013). “Multicrop Production Models with Multinomial Logit Acreage Shares”. *Environmental and Resource Economics*, 59(4), pp. 537–559.

Chambers, R. G. and R. E. Just (1989). “Estimating Multioutput Technologies”. *American Journal of Agricultural Economics*, 71(4), pp. 980–995.

Chavas, J. and M. Holt (1990). “Acreage Decisions under Risk: The Case of Corn and Soybeans”. *American Journal of Agricultural Economics*, 72(3), pp. 529–538.

Chembezi, D. M. and A. W. Womack (1992). “Regional Acreage Response For U.S. Corn and Wheat: The Effects Of Government Programs”. *Southern Journal of Agricultural Economics*, 24(1), pp. 187–198.

Chen, D., D. Abler, D. Zhou, X. Yu, and W. Thompson (2016). “A Meta-analysis of Food Demand Elasticities for China”. *Applied Economic Perspectives and Policy*, 38(1), pp. 50–72.

Chomitz, K. M. and D. A. Gray (1996). “Roads, Land Use, and Deforestation: A Spatial Model Applied to Belize”. *The World Bank Economic Review*, 10(3), pp. 487–512.

Costinot, A., D. Donaldson, and C. B. Smith (2016). “Evolving Comparative Advantage and the Impact of Climate Change in Agricultural Markets: Evidence from 1.7 Million Fields around the World”. *Journal of Political Economy*, 124(1), pp. 205–248.

Costinot, A. and A. Rodríguez-Clare (2014). “Trade Theory with Numbers: Quantifying the Consequences of Globalization”. In: *Handbook of International Economics*. Ed. by E. Helpman, K. Rogoff, and G. Gopinath. Vol. 4. Amsterdam: Elsevier. Chap. 4, pp. 197–261.

Costinot, A. and J. Vogel (2015). “Beyond Ricardo: Assignment Models in International Trade”. *Annual Review of Economics*, 7, pp. 31–62.

Dekle, R., J. Eaton, and S. Kortum (2007). “Unbalanced Trade”. *The American Economic Review*, 97(2), pp. 351–355.

Dornbusch, R., S. Fischer, and P. A. Samuelson (1977). “Comparative Advantage, Trade, and Payments in a Ricardian Model with a Continuum of Goods”. *The American Economic Review*, 67(5), pp. 823–839.

Eaton, J. and S. Kortum (2002). “Technology, Geography, and Trade”. *Econometrica*, 70(5), pp. 1741–1779.

Erb, K.-H., C. Lauk, T. Kastner, A. Mayer, M. C. Theurl, and H. Haberl (2016). “Exploring the biophysical option space for feeding the world without deforestation”. *Nature Communications*, 7(11382).

Fally, T. and J. Sayre (2017). “Commodity Trade Matter”. mimeo UC Berkeley.

Farrokhi, F. (2017). “Global Sourcing in Oil Markets”.

Feng, H. and B. A. Babcock (2010). “Impacts of Ethanol on Planted Acreage in Market Equilibrium”. *American Journal of Agricultural Economics*, 92(3), pp. 789–802.

Fritz, S., L. See, I. McCallum, C. Schill, M. Obersteiner, M. van der Velde, H. Boettcher, P. Havlík, and F. Achard (2011). “Highlighting continued uncertainty in global land cover maps for the user community”. *Environmental Research Letters*, 6(4). 044005.

Gao, G. (2012). “World Food Demand”. *American Journal of Agricultural Economics*, 94(1), pp. 25–51.

Golan, A., G. Judge, and S. Robinson (1994). “Recovering Information from Incomplete or Partial Multisectoral Economic Data”. *Review of Economics and Statistics*, 76(3), pp. 541–549.

Gouel, C. and H. Guimbard (forthcoming). “Nutrition transition and the structure of global food demand”. *American Journal of Agricultural Economics*.

Haile, M. G., M. Kalkuhl, and J. von Braun (2016). “Worldwide Acreage and Yield Response to International Price Change and Volatility: A Dynamic Panel Data Analysis for Wheat, Rice, Corn, and Soybeans”. *American Journal of Agricultural Economics*, 98(1), pp. 172–190.

Harrison, W., J. Horridge, and K. Pearson (2000). “Decomposing simulation results with respect to exogenous shocks”. *Computational Economics*, 15(3), pp. 227–249.

Havlík, P., H. Valin, M. Herrero, M. Obersteiner, E. Schmid, M. C. Rufino, A. Mosnier, P. K. Thornton, H. Bottcher, R. T. Conant, S. Frank, S. Fritz, S. Fuss, F. Kraxner, and A. Notenbaert (2014). “Climate change mitigation through livestock system transitions”. *Proceedings of the National Academy of Sciences*, 111(10), pp. 3709–3714.

Head, K. and T. Mayer (2014). “Gravity Equations: Workhorse, Toolkit, and Cookbook”. In: *Handbook of International Economics*. Ed. by E. Helpman, K. Rogoff, and G. Gopinath. Vol. 4. Amsterdam: Elsevier. Chap. 3, pp. 131–195.

Helpman, E., M. J. Melitz, and Y. Rubinstein (2008). “Estimating Trade Flows: Trading Partners and Trading Volumes”. *The Quarterly Journal of Economics*, 123(2), pp. 441–487.

Helpman, E., K. Rogoff, and G. Gopinath, eds. (2014). *Handbook of International Economics*. Vol. 4. Amsterdam: Elsevier.

Hendricks, N. P., A. Smith, and D. A. Sumner (2014). “Crop Supply Dynamics and the Illusion of Partial Adjustment”. *American Journal of Agricultural Economics*, 96(5), pp. 1469–1491.

Hennessy, D. A. (2006). “On Monoculture and the Structure of Crop Rotations”. *American Journal of Agricultural Economics*, 88(4), pp. 900–914.

Hertel, T. W., N. Ramankutty, and U. L. C. Baldos (2014). “Global market integration increases likelihood that a future African Green Revolution could increase crop land use and CO_2 emissions”. *Proceedings of the National Academy of Sciences*, 111(38), pp. 13799–13804.

IIASA/FAO (2012). *Global Agro-ecological Zones (GAEZ v3.0)*. IIASA, Laxenburg, Austria and FAO, Rome, Italy.

Keeney, R. and T. W. Hertel (2009). “The Indirect Land Use Impacts of United States Biofuel Policies: The Importance of Acreage, Yield, and Bilateral Trade Responses”. *American Journal of Agricultural Economics*, 91(4), pp. 895–909.

Knudsen, O. K. and P. L. Scandizzo (1982). “The Demand for Calories in Developing Countries”. *American Journal of Agricultural Economics*, 64(1), pp. 80–86.

Leclère, D., P. Havlík, S. Fuss, E. Schmid, A. Mosnier, B. Walsh, H. Valin, M. Herrero, N. Khabarov, and M. Obersteiner (2014). “Climate change induced transformations of agricultural systems: insights from a global model”. *Environmental Research Letters*, 9(12), p. 124018.

Lee, D. R. and P. G. Helmberger (1985). “Estimating Supply Response in the Presence of Farm Programs”. *American Journal of Agricultural Economics*, 67(2), pp. 193–203.

Lichtenberg, E. (1989). “Land Quality, Irrigation Development, and Cropping Patterns in the Northern High Plains”. *American Journal of Agricultural Economics*, 71(1), pp. 187–194.

Lin, W. and R. Dismukes (2007). “Supply Response under Risk: Implications for Counter-Cyclical Payments’ Production Impact”. *Review of Agricultural Economics*, 29(1), pp. 64–86.

Mendelsohn, R., W. D. Nordhaus, and D. Shaw (1994). “The impact of global warming on agriculture: a Ricardian analysis”. *The American economic review*, 84(4), pp. 753–771.

Miao, R., M. Khanna, and H. Huang (2016). “Responsiveness of Crop Yield and Acreage to Prices and Climate”. *American Journal of Agricultural Economics*, 98(1), pp. 191–211.

Miller, D. J. and A. J. Plantinga (1999). “Modeling Land Use Decisions with Aggregate Data”. *American Journal of Agricultural Economics*, 81(1), pp. 180–194.

Nelson, G. C., H. Valin, R. D. Sands, P. Havlík, H. Ahammad, D. Deryng, J. Elliott, S. Fujimori, T. Hasegawa, E. Heyhoe, P. Kyle, M. V. Lampe, H. Lotze-Campen, D. M. d’Croz, H. van Meijl, D. van der Mensbrugghe, C. Müller, A. Popp, R. Robertson, S. Robinson, E. Schmid, C. Schmitz, A. Tabeau, and D. Willenbockel (2014). “Climate change effects on agriculture: Economic responses to biophysical shocks”. *Proceedings of the National Academy of Sciences*, 111(9), pp. 3274–3279.

Orazem, P. F. and J. A. Miranowski (1994). “A Dynamic Model of Acreage Allocation with General and Crop-Specific Soil Capital”. *American Journal of Agricultural Economics*, 76(3), pp. 385–395.

Peeters, L. and Y. Surry (1993). “Estimating feed utilisation matrices using a cost function approach”. *Agricultural Economics*, 9(2), pp. 109–118.

Porteous, O. C. (2017). “High Trade Costs and Their Consequences: An Estimated Model of African Agricultural Storage and Trade”.

Ramankutty, N. and J. A. Foley (1999). “Estimating historical changes in global land cover: Croplands from 1700 to 1992”. *Global Biogeochemical Cycles*, 13(4), pp. 997–1027.

Randhir, T. O. and T. W. Hertel (2000). “Trade Liberalization as a Vehicle for Adapting to Global Warming”. *Agricultural and Resource Economics Review*, 29(2), pp. 159–172.

Rao, J. M. (1989). “Agricultural supply response: A survey”. *Agricultural Economics*, 3(1), pp. 1–22.

Reilly, J. M. and N. Hohmann (1993). “Climate Change and Agriculture: The Role of International Trade”. *The American Economic Review*, 83(2), pp. 306–312.

Roberts, M. J. and W. Schlenker (2013). “Identifying Supply and Demand Elasticities of Agricultural Commodities: Implications for the US Ethanol Mandate”. *The American Economic Review*, 103(6), pp. 2265–2295.

Rosenzweig, C. and M. L. Parry (1994). “Potential impact of climate change on world food supply”. *Nature*, 367(6459), pp. 133–138.

Rude, J. and K. Meilke (2000). “Implications of CAP Reform for the European Union’s Feed Sector”. *Canadian Journal of Agricultural Economics*, 48(4), pp. 411–420.

Rutherford, T. F. (2002). *Lecture Notes on Constant Elasticity Functions*. mimeo. University of Colorado.

Scott, P. T. (2013). “Indirect Estimation of Yield-Price Elasticities”.

— (2014). *Dynamic Discrete Choice Estimation of Agricultural Land Use*. Working Paper TSE-526. TSE.

Seale Jr., J. L. and A. Regmi (2006). “Modeling International Consumption Patterns”. *Review of Income and Wealth*, 52(4), pp. 603–624.

Sotelo, S. (2015). *Domestic Trade Frictions and Agriculture*. Discussion Paper 641. University of Michigan.

Stavins, R. N. and A. B. Jaffe (1990). “Unintended Impacts of Public Investments on Private Decisions: The Depletion of Forested Wetlands”. *The American Economic Review*, 80(3), pp. 337–352.

Subramanian, S. and A. Deaton (1996). “The Demand for Food and Calories”. *The Journal of Political Economy*, 104(1), pp. 133–162.

Tegene, A., W. E. Huffman, and J. A. Miranowski (1988). “Dynamic Corn Supply Functions: A Model with Explicit Optimization”. *American Journal of Agricultural Economics*, 70(1), pp. 103–111.

Tsigas, M. E., G. B. Frisvold, and B. Kuhn (1997). “Global climate change and agriculture”. In: *Global Trade Analysis: Modeling and Applications*. Ed. by T. W. Hertel. Cambridge University Press. Chap. 11, pp. 280–304.

Wiebe, K., H. Lotze-Campen, R. Sands, A. Tabeau, D. van der Mensbrugghe, A. Biewald, B. Bodirsky, S. Islam, A. Kavallari, D. Mason-D’Croz, C. Müller, A. Popp, R. Robertson, S. Robinson, H. van Meijl, and D. Willenbockel (2015). “Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios”. *Environmental Research Letters*, 10(8), p. 085010.

Wu, J. and K. Segerson (1995). “The Impact of Policies and Land Characteristics on Potential Groundwater Pollution in Wisconsin”. *American Journal of Agricultural Economics*, 77(4), pp. 1033–1047.