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THE CRUCIAL ROLE OF INTERNATIONAL TRADE IN ADAPTATION TO CLIMATE CHANGE

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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 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 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 larger welfare losses from climate change when adjustments in trade flows are constrained versus when they are not.

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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 in mitigating 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. For example, reallocating crop production within a country to areas where yields increase, despite adverse effects on average, may go a long way in attenuating the initial yield loss. Similarly, growing different crops, more adapted to the new climate, may contribute to reducing the adverse effects of climate change if crop demand for feeding people and 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. If, on the other hand, reallocation of crop area and demand substitutability between crops is limited, then international trade may play a large role in demand and supply adjustments.

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. 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. 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, the parameters are the price elasticity of total agricultural demand and the elasticities of substitution between agricultural products for food and feed demand. On the supply side, the parameters are the acreage elasticity and the yield elasticity (in sensitivity analysis). Finally, the trade elasticity governs the flexibility to adjust between demand and supply. 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, tripling the welfare losses, while forcing the exported share of crops under climate change to be the same as the current share would affect welfare only marginally. 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 related to their experimental design that involves a very specific definition of the constrained trade counterfactual, and a combination of model assumptions and parameter estimations leading to very elastic demand and supply for food, three times higher than usual estimates in the literature. With large domestic adjustments, trade adjustments play a small role. On the modeling side, the demand function uses a form implying a unit price elasticity for the entire food bundle, and it is assumed for supply that cropland can be extended over "unused" lands without any other opportunity costs than the production costs, neglecting the fact that lands not used for planting the crops under study have valuable uses and will not be used for these crops without significant opportunity costs. For the estimations, they estimate the three key behavioral parameters of the model on cross-sectional information using the restrictions imposed by the model equations. The simplicity of the model implies that the mapping between theory and data leaves many gaps that likely explain the unusually elastic demand and supply parameters. We discuss the challenges related to such an estimation bridging theory and data in the paper, which motivates our choice of calibrating our model on a literature review. The inelasticity of agricultural good demand is a well-established empirical result (Fally and Sayre, 2018; 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 an influential margin of adjustment. The model aims to represent all crops with a significant role in final demand and agricultural land use and thus includes 35 crops. 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's (2002) modeling of trade in homogeneous goods (an acreage modeling also recently used in Sotelo, 2015). Its key element is the assumption 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 of the difficulty of properly modeling these decisions in a static framework (see Scott, 2014, for the example of a dynamic modeling of land-use extension). However, given that we represent pastures and almost all crops, we account for the bulk of the likely counterfactual land use changes.

This paper can be linked to 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 (2018) and Farrokhi (2017) show that accounting for the specificities of commodities leads to higher measured gains from trade. Commodities—in our case, livestock and crops—tend to be produced using sector-specific, non-tradable resources—in our case land. These commodities have low supply elasticities because of their use of specific assets and low demand elasticities because of their essential role in downstream sectors. These features explain why commodities 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 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 other on international adaption to climate change in agriculture. Section 3 develops the general equilibrium model and makes clear, using 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 each adjustment margin, which allows us to analyze its influence on the role of international trade in adaptation to climate change. 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 that there is an unobserved within-field heterogeneity explaining why 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. A first approach (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 (an approach similar to Dornbusch et al., 1977, Ricardian trade model). This makes working with more than two crops cumbersome. 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 cannot 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), prevent full specialization on some crops with a convex cost function, implying decreasing return to scale when specializing in one crop. This strategy yields very flexible representations, but the convexity of the costs tends to be difficult to interpret. Second, models where acreage or land-use shares are represented with systems of multinomial logit equations.[1] These models have two origins. They have emerged either as

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[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.

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 been used mainly for analyzing land-use choices, but not for acreage choices.

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 applied here with earlier work using extreme value distributions. The role of the stochastic specification is fundamentally different than 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. However, the implications of this difference are 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. Randhir and Hertel (2000) are an exception, reaching the counterintuitive conclusion that the adjustments facilitated by international trade could have detrimental welfare effects. This result illustrates potential outcomes in a second-best world 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, agricultural policies empirically tend to evolve with comparative advantages and market conditions (Anderson et al., 2013). Thus, they are unlikely to stay the same with climate change. Consequently, our model abstains 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 crop yields after climate change involves assuming a weighting scheme for the local yield changes. The weighting scheme adopted is usually based on current crop production, which negates the possibility 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 interest with papers using either gridded information or different land classes based on agroecological zones frameworks (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 connection with the theoretical and empirical land-use literature. Reciprocally, the land-use literature dealing with climate change tends to neglect market, especially international trade, adaptations (Mendelsohn et al., 1994). A couple of papers using global models emphasize that trade patterns in agricultural products are likely to change a lot with climate change, without precisely analyzing the adaptive role of international trade (Ahammad et al., 2015; Leclère et al., 2014). 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, and by representing livestock with the associated feed consumption, in particular pastures that account for a large part of land uses.

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 $k = \mathrm{l}$. 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, which we call grass and index by $k = \mathrm{g}$, is assumed to be not tradable, because it represents forage crops that are directly grazed by animals and fodder crops (e.g., alfalfa hay) that have too low of a value-to-weight ratio to be tradable.[2] 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 $\omega \in [0, 1]$. The outside good is freely traded and plays the role of a numeraire.

Preferences The representative household in country i has quasi-linear preferences over the consumption of the 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. This 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:

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

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[2] International trade of hay is growing but remains sufficiently low that we can neglect it here.

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

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

where $\sigma > 0$ 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.

Technology

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

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

where Q_i^0 is the quantity produced, N_i^0 is the corresponding labor demand, and $A_i^0 > 0$ is labor 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 are too high for growing them. This is consistent with the fact that pastures are more likely to be located on lands that are not the most suitable for crop production because of short growing seasons, limited water access or steep slope. However, this assumption neglects the fact that pastures and hay fields are actively managed and are not simply rangelands. This problem 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 of illegal deforestation activities. These decisions would be challenging to model and to estimate

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[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 $x > 0$.

at a global scale (Scott, 2014) and so are neglected here. This choice could create a possible bias by not representing one 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 intensification. However, we assess the sensitivity of the results to this crucial assumption.

Livestock Livestock products are produced by combining feed and labor:

$$Q_i^1 = \min\left(\frac{x_i}{\mu_i}, \frac{N_i^1}{\nu_i^1}\right), \tag{6}$$

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 feed 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:

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

where $\varsigma > 0$ is the elasticity of substitution between the various feed crops and $\beta_i^{k,\text{feed}} \geq 0$ 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.

Except for the outside good, 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 to sell a variety of sector k. The absence of arbitrage opportunities implies that

$$p_{ij}^k = \tau_{ij}^k p_i^k \text{ for all } k \in \mathcal{K}^a, \tag{8}$$

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.

Agricultural products, having a higher average level of protection than products in other sectors, 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 economic 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:

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

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:

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

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

Production Zero profit, absence of trade barriers, and the numeraire assumption in the non-agricultural sector imply

$$A_i^0 = w_i, \tag{13}$$

which will be used below to substitute w_i away.

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

$$p_i^{\mathrm{l}} = \nu_i^{\mathrm{l}} A_i^0 + \mu_i P_i^{\mathrm{feed}}, \tag{14}$$

$$x_i^k = \beta_i^{k,\mathrm{feed}} \left(\frac{P_i^k}{P_i^{\mathrm{feed}}} \right)^{-\varsigma} \mu_i Q_i^{\mathrm{l}}, \tag{15}$$

$$P_i^{\mathrm{feed}} = \left[\sum_{k \in \mathcal{K}^c} \beta_i^{k,\mathrm{feed}} \left(P_i^k \right)^{1-\varsigma} \right]^{1/(1-\varsigma)}, \tag{16}$$

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

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

$$Q_i^{fk}(\omega) = A_i^{fk}(\omega) = N_i^{fk}(\omega) / \nu_i^k. \tag{17}$$

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

$$p_i^k Q_i^{fk}(\omega) - A_i^0 N_i^{fk}(\omega) = \left(p_i^k - A_i^0 \nu_i^k\right) A_i^{fk}(\omega), \tag{18}$$

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

$$r_i^k \equiv p_i^k - A_i^0 \nu_i^k \tag{19}$$

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

$$\pi_i^{fk} = \frac{\left(r_i^k A_i^{fk}\right)^\theta}{\sum_{l \in \mathcal{K}^c, r_i^l \geq 0} \left(r_i^l A_i^{fl}\right)^\theta}. \tag{20}$$

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:

$$Q_i^{fk} = s_i^f \pi_i^{fk} \operatorname{E}\left[A_i^{fk}(\omega) \,|\, r_i^k A_i^{fk}(\omega) \in \arg\max_{l \in \mathcal{K}^c} r_i^l A_i^{fl}(\omega)\right]. \tag{21}$$

From the standard properties of the Fréchet distribution we have

$$E\left[r_i^k A_i^{fk}(\omega) \,|\, r_i^k A_i^{fk}(\omega) \in \arg\max_{l \in \mathcal{K}^c} r_i^l A_i^{fl}(\omega)\right] = \left[\sum_{l \in \mathcal{K}^c, r_i^l \geq 0} \left(r_i^l A_i^{fl}\right)^\theta\right]^{1/\theta}, \tag{22}$$

so

$$Q_i^{fk} = s_i^f A_i^{fk} \left(\pi_i^{fk}\right)^{(\theta-1)/\theta}, \tag{23}$$

and country-level production is

$$Q_i^k = \sum_{f \in \mathcal{F}_i} s_i^f A_i^{fk} \left(\pi_i^{fk}\right)^{(\theta-1)/\theta}. \tag{24}$$

Similarly, the total land rents from growing crop k are

$$R_i^k = \sum_{f \in \mathcal{F}_i} s_i^f \pi_i^{fk} E\left[r_i^k A_i^{fk}(\omega) \,|\, r_i^k A_i^{fk}(\omega) \in \arg\max_{l \in \mathcal{K}^c} r_i^l A_i^{fl}(\omega)\right] = r_i^k Q_i^k. \tag{25}$$

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

$$\frac{\partial \ln Q_i^k}{\partial \ln p_i^k} = (\theta - 1) \frac{p_i^k}{r_i^k} \sum_{f \in \mathcal{F}_i} \left(1 - \pi_i^{fk}\right) \frac{Q_i^{fk}}{Q_i^k}. \tag{26}$$

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 conversion of 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 acreages. For a crop with very small acreages, $\pi_i^{fk}\approx 0$, the elasticity is $(\theta-1)\,p_i^k/r_i^k$. The elasticity decreases when acreages increase, eventually reaching 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

$$P_i^k = \left[\sum_{j\in\mathcal{I}} \beta_{ji}^k \left(\tau_{ji}^k p_j^k\right)^{1-\sigma}\right]^{1/(1-\sigma)} \quad \text{for all } k \in \mathcal{K}^a, \tag{27}$$

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

$$X_i^k/P_i^k = C_i^k + \mathbf{1}_{k\in\mathcal{K}^c}\left(x_i^k\right) \text{ for all } k \in \mathcal{K}^a \tag{28}$$

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

$$X_{ji}^k = \beta_{ji}^k \left(\frac{\tau_{ji}^k p_j^k}{P_i^k}\right)^{1-\sigma} X_i^k. \tag{29}$$

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

$$p_i^k Q_i^k = \sum_{j\in\mathcal{I}} X_{ij}^k. \tag{30}$$

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

$$E_i = A_i^0 N_i + \sum_{k\in\mathcal{K}^c} r_i^k Q_i^k + \Delta_i. \tag{31}$$

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}), consumption price (P_i^k), total imports (X_i^k), bilateral exports (X_{ij}^k), producer price (p_i^k), and expenditures (E_i) such that equations (9)–(12), (14)–(16), (19), (20), (24), and (27)–(31) hold.

3.3 Equilibrium in relative changes

To make the data necessary to calibrate this model explicit, we 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 one source of exogenous shocks: 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 in a country 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 a country's crop is considered imperfectly substitutable for 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 goods. $\alpha_i^{k,\text{feed}} = P_i^k x_i^k / P_i^{\text{feed}} x_i$ 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

$$\hat{p}_i^k = \phi_i^{k,\text{labor}} + \phi_i^{k,\text{land}} \hat{r}_i^k + \phi_i^{k,\text{feed}} \hat{P}_i^{\text{feed}}. \tag{32}$$

To allow for the possibility that fields may have zero potential yields in some crops in the baseline but positive yields 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

$$\hat{Q}_i^k = \sum_{f \in \mathcal{F}_i} \frac{s_i^f A_i^{fk\prime}}{Q_i^k} \frac{\left(r_i^k \hat{r}_i^k A_i^{fk\prime} \right)^{\theta - 1}}{\left[\sum_{l \in \mathcal{K}^c} \left(r_i^l \hat{r}_i^l A_i^{fl\prime} \right)^{\theta} \right]^{(\theta - 1)/\theta}} \text{ for all } k \in \mathcal{K}^c. \tag{33}$$

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

$$\hat{P}_i = \left[\sum_{k \in \mathcal{K}^a} \alpha_i^k \left(\hat{P}_i^k \right)^{1-\kappa} \right]^{1/(1-\kappa)}, \tag{34}$$

$$\hat{C}_i^k = \left(\hat{P}_i^k \right)^{-\kappa} \left(\hat{P}_i \right)^{\kappa - \epsilon} \text{ for all } k \in \mathcal{K}^a, \tag{35}$$

$$P_i^0 C_i^0 \hat{C}_i^0 = E_i \hat{E}_i - P_i C_i \left(\hat{P}_i \right)^{1-\epsilon}, \tag{36}$$

$$\hat{x}_i^k = \left(\hat{P}_i^k / \hat{P}_i^{\text{feed}} \right)^{-\varsigma} \hat{Q}_i^1 \text{ for all } k \in \mathcal{K}^c, \tag{37}$$

$$\hat{P}_i^{\text{feed}} = \left[\sum_{k \in \mathcal{K}^c} \alpha_i^{k,\text{feed}} \left(\hat{P}_i^k \right)^{1-\varsigma} \right]^{1(1-\varsigma)}, \tag{38}$$

$$\hat{P}_i^k = \left[\sum_{j \in \mathcal{I}} \alpha_{ji}^k \left(\hat{p}_j^k \right)^{1-\sigma} \right]^{1/(1-\sigma)}, \tag{39}$$

$$X_i^k \hat{X}_i^k = P_i^k C_i^k \hat{P}_i^k \hat{C}_i^k + \mathbf{1}_{k \in \mathcal{K}^c} \left(P_i^k x_i^k \hat{P}_i^k \hat{x}_i^k \right), \tag{40}$$

$$\hat{X}_{ji}^k = \left(\hat{p}_j^k / \hat{P}_i^k \right)^{1-\sigma} \hat{X}_i^k, \tag{41}$$

$$p_i^k Q_i^k \hat{p}_i^k \hat{Q}_i^k = \sum_{j \in \mathcal{I}} X_{ij}^k \hat{X}_{ij}^k, \tag{42}$$

$$E_i \hat{E}_i = A_i^0 N_i + \sum_{k \in \mathcal{K}^c} R_i^k \hat{r}_i^k \hat{Q}_i^k. \tag{43}$$

These equations make clear the information needed for calibrating the model, and the mapping with the data is discussed in section 4. Only one aspect deserves further discussion here: the calibration of the land rent per unit of production, r_i^k, and the volume of crop production, Q_i^k, in equation (33). We show now that given field-level potential yields, A_i^{fk}, and aggregate moments, we can uniquely recover these initial values. Using equations (20), (24), and (25), we have

$$\left(r_i^k\right)^{-\theta} = \left(R_i^k\right)^{-1} \sum_{f \in \mathcal{F}_i} s_i^f \left(A_i^{fk}\right)^\theta \left[\sum_{l \in \mathcal{K}^c} \left(r_i^l A_i^{fl}\right)^\theta\right]^{(1-\theta)/\theta}. \tag{44}$$

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, $\left\{r_i^k > 0 | k \in \mathcal{K}^c, R_i^k > 0\right\}$, 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 (20) and the initial production levels, Q_i^k, from equation (24).

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 we rely on for calibration 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 the 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 also means 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 (32)–(43) 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] The household expenditure function is

$$e\left(P_i^0, P_i, U_i\right) = P_i^0 U_i + \beta_i \left(P_i^0\right)^\epsilon \begin{cases} P_i^{1-\epsilon}/(1-\epsilon) & \text{if } \epsilon \neq 1, \\ \left[1 - \ln\left(\beta_i P_i^0 / P_i\right)\right] & \text{if } \epsilon = 1. \end{cases} \tag{45}$$

The equivalent variation expressed in terms of variables in relative changes is

$$EV_i = e\left(P_i^0, P_i, U_i'\right) - e\left(P_i^0, P_i, U_i\right) = P_i^0 C_i^0 \left(\hat{C}_i^0 - 1\right) + P_i C_i \begin{cases} \left(\hat{C}_i^{1-1/\epsilon} - 1\right)/(1 - 1/\epsilon) & \text{if } \epsilon \neq 1, \\ \ln \hat{C}_i & \text{if } \epsilon = 1. \end{cases} \tag{46}$$

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

$$\mathrm{d}\,EV_i = \underbrace{\sum_{k \in \mathcal{K}^a, j \in \mathcal{I}} \left(X_{ij}^k \,\mathrm{d}\ln p_i^k - X_{ji}^k \,\mathrm{d}\ln p_j^k\right)}_{\text{Terms-of-trade effects}} + \underbrace{\sum_{f \in \mathcal{F}_i, k \in \mathcal{K}^c} r_i^k Q_i^{fk} \,\mathrm{d}\ln A_i^{fk}}_{\text{Productivity effects}}. \tag{47}$$

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[4] In this setting of a *de facto* partial equilibrium model where the price of the outside good is constant and the representative household has quasi-linear utility, the equivalent variation is equal to the consumer surplus and the compensating variation.

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 the welfare changes for small changes. The 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 the first-order approximation in equation (47) valid. 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:

$$EV_i = \sum_{k \in \mathcal{K}^a, j \in \mathcal{I}} \int_{t=0}^{1} \left(X_{ij}^k(t) \frac{\mathrm{d} \ln p_i^k}{\mathrm{d} t} - X_{ji}^k(t) \frac{\mathrm{d} \ln p_j^k}{\mathrm{d} t} \right) \mathrm{d} t + \sum_{f \in \mathcal{F}_i, k \in \mathcal{K}^c} \int_{t=0}^{1} r_i^k(t) Q_i^{fk}(t) \frac{\mathrm{d} \ln A_i^{fk}}{\mathrm{d} t} \mathrm{d} t, \tag{48}$$

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: $t A_i^{fk\prime} + (1-t) A_i^{fk}$. 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 to represent most agricultural commodities for several reasons. First, if almost all the sources of calories are included in the model, then the top elasticity ϵ can be interpreted as the opposite of 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 an even smaller share of trade. Lastly, climate change will affect all crops differentially. So, neglecting some crops with non-negligible land use would imply 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 an even higher share of agricultural land uses when pastures are accounted for.

4.1 Behavioral parameters

After having properly harmonized the concept and definition of the parameters in the model and available estimates, we rely on a literature review to select the behavioral parameters. We have chosen this strategy because there are important difficulties that probably make it impossible to estimate these parameters in a cross-country setting structurally. These difficulties, which have not been addressed in CDS, likely explain why their estimated demand and supply elasticities far

Table 2: List of sample countries and crops

Country	Share of world ag. area (%)[a]	Share of world output (%)[b]	Country	Share of world ag. 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] Based on agricultural area in Ramankutty and Foley (1999) extended to 2007. [b] Model values for the initial equilibrium based on FAOSTAT and GTAP as described in Appendix D.

exceed usual estimates. The main difficulty is related to the fact that the mapping between the model and the available data leaves too many gaps.

On the demand side, while it makes sense in the model to abstract from existing policies, that are unlikely to stay the same, and from income effects, that are likely to be small, it is not reasonable to neglect them in the estimation of elasticities, given that both drive a lot of the variations in final demand. Despite decades of trade negotiations, distortions remain prevalent in the agricultural sector and should not be neglected when estimating gravity equations for these sectors. *Ad-valorem* equivalents of these policies can be calculated but are poor proxies for the existing policies that often take the form of specific tariffs and tariff-rate quotas, two features specific to agricultural goods that prevent the transmission of import prices to the domestic markets and that are inconsistent with a multiplicative representation of distortions. So, building consumer prices from producer prices as done in CDS is likely to lead to biased estimates of the prices actually faced by consumers. Domestic demand policies are also an important driver of the differences of demand across countries. One obvious example is the biofuel policies that are active in many countries. By mandating that large amounts of crop supply be directed to fuel consumption, these policies artificially raise demand with very large effects on some crops (e.g., one-third of U.S. maize production and one-third of E.U. vegetable oil supply). Lastly, it is well identified that diets evolve with income toward higher consumption of animal-based food products, oil and fats, and sweeteners (Gouel and Guimbard, forthcoming). Given that animal-based food products require crops for their production, differences in their demand have large effects on the total demand for many crops, explaining a lot of the differences in crop consumption between rich and poor countries.

On the supply side, the main problem is the absence of statistics at the global level on physical acreages by crop that could be mapped to the model variables. The only available statistics, from FAOSTAT and used in the estimations in CDS, concern harvested areas, that is, the physical areas planted with a crop multiplied by the number of times they are harvested in the year. In tropical countries, the same fields can be planted and harvested several times a year, so physical and harvested areas can be very different. In the case of Bangladesh in 2010, the sum of all harvested areas (which does not include pastures) is 15.2 million hectares, more than the country area and almost double the FAOSTAT figure for area under arable land and permanent crops. So, each field is harvested twice a year on average, but the cropping intensity by crop is unknown. Our modeling framework is robust to multiple cropping as long as the cropping intensity is uniform across the fields within a country, because it can be represented by a crop-country productivity shifter (Appendix B). However, without information about the cropping intensity by crop, it is not possible to estimate the supply-side of the model. The estimation in CDS suffers from this problematic mapping between model and data.

Since cross-section estimations are not feasible for this model, we rely on existing estimations, mostly at the country level, of the elasticities of interest and detail below their sources and how they map to the elasticities in the model.

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, 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 with income. However, this literature does not provide aggregate elasticities at the country level. The second set of relevant literature does, since it is concerned with country-level estimates of final demand for food. Seale and Regmi (2006) and Gao (2012) estimate, respectively, a complete demand system and a reduced-form food demand at the country level on cross-sectional ICP data. They confirm that the price elasticity decreases in absolute value with income also at the country level. Seale and Regmi (2006, Table 4) report uncompensated elasticities ranging 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 higher for India 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 in Gao's research is that the elasticities concerned processed food products; 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 nested below the quasi-linear utility function precludes a perfect representation as calories.

Following these considerations, we adopt $\epsilon = 0.2$. This parameter plays a crucial role in the results because it determines whether adaptation to climate change occurs through a reduction in demand for agricultural products or through higher prices that 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 this elasticity 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 (34)–(35), this elasticity is

$$\frac{\partial \ln C_i^k}{\partial \ln P_i^k} = -\kappa + (\kappa - \epsilon)\,\alpha_i^k. \tag{49}$$

This formula implies that the demand elasticity is bounded between $-\kappa$ for a budget share close to 0 and $-\epsilon$ for a budget share 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 using household survey data, but the elasticities estimated at the country-level using 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 (37) and (38):

$$\frac{\partial \ln x_i^k}{\partial \ln P_i^k} = -\varsigma\left(1 - \alpha_i^{k,\text{feed}}\right). \tag{50}$$

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. These elasticities 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. 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 ($1 - \sigma$ in the model), −5. But, we should note that there is a large variety of estimates in the gravity literature. For example, Caliendo and Parro's (2015) preferred estimate of the trade elasticity for agricultural products is −9, almost twice as large CDS' estimate, which would lead to even higher trade reallocations, a situation considered in section 6.

Degree of within-field heterogeneity From equation (26), 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 which is likely related to the regular changes in farm policies and thus farmers' incentives. Nevertheless, the estimates 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 in Appendix D). 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

Expressing the model in deviation from benchmark in section 3.3 allows us to identify the minimum set of information needed to calibrate the model. As with any general equilibrium model, we need aggregate value information at the country or sector level, such as final expenditures, trade flows, production values, and various budget shares. Information on potential yields under current climate and under climate change are taken from the GAEZ project (IIASA/FAO, 2012), which provides this information at the 5-arcminute level. Since this level of detail would result in a very large and difficult-to-solve model, we aggregate the yield information at the 1-degree level, which results in 11,801 fields, and test the effect of this aggregation in sensitivity analysis. Most agricultural statistics are taken from FAOSTAT, but we also need additional information not available in FAOSTAT datasets. We use Ramankutty and Foley (1999) for the extent of each field that is devoted to agricultural land. All other data comes from the GTAP database, in particular the value of livestock production and the share of land in production costs. Details about the various data and how they are combined are provided in Appendix D.

5 Quantitative results

5.1 Main counterfactual results

The main counterfactual consists in changing the potential yields, A_i^{fk}, from their values under current climate to their values at the 2080s horizon under climate change from the emission scenario A1FI. The 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 5 report welfare changes in percentage of GDP and its decomposition following equation (48) between terms-of-trade and productivity effects. The last nine lines report the average results for regional aggregates and for the world, with welfare calculated for the world (indexed w), and similarly for aggregates, as

$$\frac{EV_w}{E_w} = \frac{\sum_{i\in\mathcal{I}} EV_i}{E_w}. \tag{51}$$

The welfare decomposition shows us that few countries experience gains related to productivity changes (column 4), and if there are gains, they tend to be rather small, with a maximum of 0.75 for Argentina. But there are countries that can benefit a lot from climate change. In these cases, the welfare 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, and 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 a large proportion of their agricultural production (e.g., Argentina, Brazil, Canada, France, the United States) tend to gain from climate change, even if they suffer from productivity losses, by shifting the burden of the adjustment to climate change to consuming countries through international prices. The opposite is also true: net-food-importing countries suffer from terms-of-trade related losses. Overall, for more than half of our individual countries, the welfare impact of terms-of-trade effects is larger than the productivity impact. The same pattern can be observed for regional aggregates: net-food-exporting regions (Latin and Northern America, and Oceania) have welfare gains because of their agricultural terms-of-trade gains. Countries with large welfare gains are not present in CDS because their elastic demand implies that price adjustments are too small for terms-of-trade effects to compensate for 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 to yield shocks. Their reliance on imports exposes them to detrimental terms-of-trade shocks. And their geographical location is the most exposed to the negative effects of climate change on yields. Bangladesh, Malaysia, and Sri Lanka are examples of this in the model.

We turn now to the specific situation of Sub-Saharan Africa, the region experiencing the largest losses, with an average loss of -21.57%. 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) and tropical cereals (millet and sorghum), because of perishability or because of the high trade costs in the region (Porteous, forthcoming). 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 for adaptation. Without initial trade, no trade can be created under an Armington structure. Because of the low flexibility of demand, domestic prices increase dramatically, driving up the planted areas despite the lower productivity, which aggravates the severity of the initial shock as more resources are pulled into producing a crop that now requires relatively much more land to produce than before. Things would have played out differently with

Table 4: Benchmark counterfactual welfare results (welfare as % of GDP)

			Welfare decomposition[b]			No adjustment on		
Country[a]	Crop output as % of total GDP (1)	Net ag. trade as % of ag. prod (2)	Ag. terms of trade (3)	Productivity change (4)	Total (5)	acreage shares (6)	bilateral import shares (7)	export shares (8)
Argentina	8.30	60.64	13.26	0.75	14.02	46.12	16.30	21.14
Australia	3.62	34.72	1.82	−0.46	1.36	4.31	2.64	2.13
Bangladesh	15.52	−31.46	−14.74	−7.18	−21.94	−44.49	−44.93	−31.23
Brazil	7.62	38.01	7.07	−3.94	3.12	8.69	9.67	4.36
Canada	3.04	25.38	2.36	0.49	2.85	6.92	−0.28	3.65
China (including Hong Kong)	9.58	−4.96	0.32	−0.96	−0.64	−6.76	−1.74	−0.41
Colombia	7.17	4.46	3.07	−7.29	−4.25	−9.54	−3.62	−5.77
Egypt	7.79	−48.13	−6.58	−3.07	−9.67	−18.66	−13.61	−12.67
Ethiopia	47.42	0.66	33.50	−1.13	32.39	93.10	−7.23	36.35
France	3.25	17.65	0.93	−0.16	0.77	1.33	0.67	1.52
Germany	2.23	−6.76	−1.03	0.04	−0.99	−2.55	−1.84	−1.04
Greece	5.82	−9.92	−6.14	−13.99	−20.23	−42.83	−28.61	−27.61
India	16.60	4.78	−1.21	−12.97	−14.25	−19.59	−19.58	−18.62
Indonesia	13.15	−7.88	−0.75	−9.03	−9.81	−17.37	−15.51	−13.82
Iran	6.24	−14.54	−2.67	−2.32	−5.00	−13.30	−10.14	−7.95
Italy	2.88	−23.40	−2.35	−1.51	−3.87	−8.99	−4.90	−4.84
Japan	1.59	−31.66	−0.79	−0.11	−0.90	−2.52	−1.35	−1.24
Kazakhstan	9.64	−1.12	−0.35	−0.63	−0.97	−0.36	−2.85	−1.71
Kenya	24.91	4.81	29.92	−4.88	25.05	47.15	−14.90	19.26
Korea, South	2.30	−48.81	−2.08	−0.12	−2.19	−6.38	−3.45	−3.23
Malaysia	8.86	−30.10	−10.50	−1.04	−11.53	−23.95	−16.93	−15.58
Mexico	3.88	−17.17	−0.35	−1.23	−1.59	−4.21	−1.92	−2.36
Morocco	13.04	−27.36	−11.88	−8.22	−20.14	−41.47	−29.58	−27.75
Netherlands	3.49	−16.07	−7.04	−0.01	−7.04	−17.06	−10.73	−7.38
Nigeria	10.63	−9.98	−7.72	−40.55	−48.57	−76.11	−94.64	−62.30
Pakistan	24.80	1.86	2.38	−2.19	0.19	0.75	−1.56	2.87
Peru	8.66	−6.52	1.51	−3.89	−2.40	−6.51	−3.76	−2.81
Philippines	13.77	−0.76	7.17	−9.80	−2.68	16.99	−2.87	−3.24
Poland	5.45	2.37	−0.12	0.19	0.07	0.95	−1.49	0.47
Romania	9.60	−1.96	−0.30	−0.90	−1.20	−1.24	−1.65	−0.95
Russia	4.67	−9.17	−0.55	−0.10	−0.64	−1.73	−2.09	−0.48
Senegal	13.93	−45.21	−20.90	−9.27	−30.19	−72.88	−72.04	−52.24
South Africa	5.04	1.43	2.15	−1.63	0.52	1.98	0.54	1.98
Spain	3.78	1.11	1.25	−1.45	−0.21	−2.12	−0.14	−0.02
Sri Lanka	6.76	−38.64	−11.47	−13.01	−24.57	−46.08	−40.14	−34.76
Thailand	8.81	20.56	0.33	−6.55	−6.25	−15.22	−5.90	−14.60
Turkey	6.61	−7.26	0.62	−1.38	−0.76	−8.20	−2.05	−0.96
Ukraine	14.73	30.53	10.64	−1.90	8.75	28.10	14.29	14.32
United Kingdom	1.70	−38.73	−1.03	0.03	−1.00	−2.57	−1.78	−1.36
United States	2.54	15.24	0.33	−0.22	0.11	0.84	0.44	0.46
Viet Nam	17.94	−1.74	0.03	−14.15	−14.18	−27.49	−17.65	−22.24
Asia	7.66	−5.93	−0.56	−2.52	−3.09	−7.72	−4.93	−4.18
Commonwealth of Independent States	6.66	−1.68	0.11	−0.22	−0.11	0.22	−1.31	0.34
Europe	3.01	−5.15	−0.85	−0.49	−1.35	−3.73	−2.37	−1.42
Latin America	7.00	23.86	5.06	−3.65	1.39	5.53	4.14	2.04
Middle East and North Africa	4.67	−38.46	−4.17	−1.61	−5.78	−14.70	−9.43	−8.54
Northern America	2.59	16.47	0.54	−0.15	0.39	1.47	0.36	0.79
Oceania	4.61	37.30	2.26	−0.62	1.64	4.74	2.70	2.82
Sub-Saharan Africa	15.06	−3.09	0.45	−21.57	−21.24	−34.21	−46.58	−29.60
World	5.03	0	0	−1.72	−1.72	−3.71	−3.02	−2.18

Notes: [a] Only countries represented individually in the model are presented here. [b] From equation (47), the sum of columns 3 and 4 gives approximately column 5. 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%.

enough initial trade: acreage in tropical roots would have been reduced, and the country would have specialized in other production and relied more on imports. With large welfare gains, Ethiopia and Kenya are two exceptions, which are also visible in figure A1 where these countries are part of the small African regions experiencing yield gains on average. For the other African countries, the lack of international trade aggravates the productivity loss by preventing reallocations to more profitable crops (this claim is proved in section 6.3).

To illustrate the role of international trade in allowing large adjustments to climate change between countries, figure 1 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. Shares of maize and rice in particular bear little resemblance to their current market shares. For the maize market, traditional exporters such as the U.S., Brazil, France, and Ukraine suffer strong yield reduction and consequentially reduce their exports. Canada, Germany, and China, located in northern latitudes, have higher maize yields. They step in to fill the gap, with the world production of maize even increasing 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). These results show that pattern of international trade flows in agricultural products may look extremely different from now because of the effects of climate change.

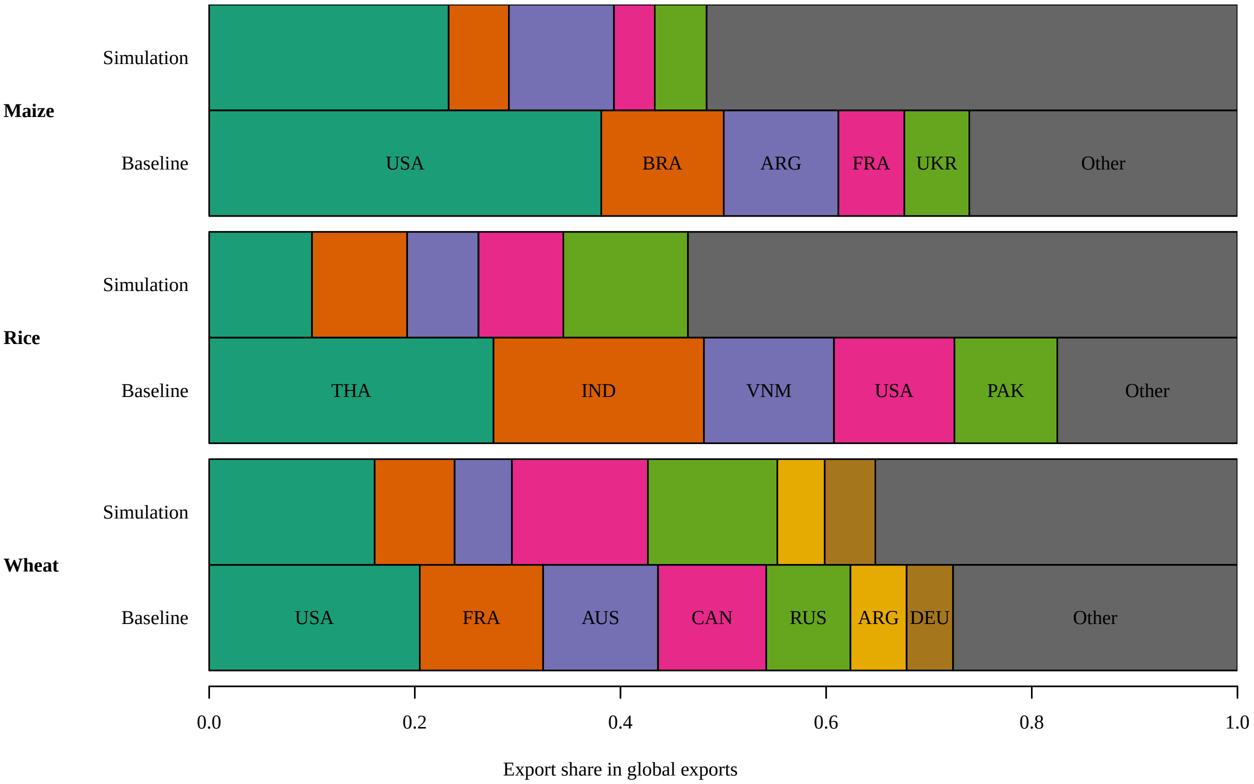

Figure 1: Changes in export shares

5.2 The role of acreage adjustments

To assess the role of acreage changes in adaptation to climate change, we follow CDS and consider a scenario where acreages cannot adjust and are fixed to their initial values. In this case, the counterfactual production is given by

$$Q_i^{k\prime} = \sum_{f\in\mathcal{F}_i} s_i^f \pi_i^{fk}\, \mathrm{E}\left[A_i^{fk\prime}(\omega)\,|\,r_i^k A_i^{fk}(\omega) \in \arg\max_{l\in\mathcal{K}^c} r_i^l A_i^{fl}(\omega)\right], \tag{52}$$

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

$$Q_i^{k\prime} = \sum_{f\in\mathcal{F}_i} s_i^f A_i^{fk\prime}\left(\pi_i^{fk}\right)^{(\theta-1)/\theta}, \tag{53}$$

and in exact hat algebra

$$\hat{Q}_i^k = \sum_{f\in\mathcal{F}_i} \hat{A}_i^{fk} \frac{Q_i^{fk}}{Q_i^k}. \tag{54}$$

This counterfactual where acreage shares stay the same is presented in column 6 of table 4. At the world level, preventing adjustments on production more than doubles the initial welfare losses. This constraint does not reverse the sign of most welfare results, it just amplifies them. Countries that tend to gain from climate change without the constraint tend to gain more with it, and vice versa for countries that tend to lose from climate change. Since gains are mostly related to terms-of-trade gains, this result implies that preventing supply adjustments from occurring exacerbates the terms-of-trade change for the benefits of the net-food-exporting countries.

5.3 The role of trade adjustments

We turn now to 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 the trade adjustments' role. We could consider restricting the adjustments in bilateral import shares, the adjustments in 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. To see how much costlier climate change would be if trade changes were 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:

$$\hat{X}_{ii}^k/\hat{p}_i^k = \hat{Q}_i^k \text{ for all } k \in \mathcal{K}^a. \tag{55}$$

This equation holds by adding ad-valorem export taxes (or subsidies), denoted δ_i^k, to the model. Three of the model equations must be adjusted accordingly: equation (39) that defines the consumer price index,

$$\hat{P}_i^k = \left[\sum_{j\in\mathcal{I}} \alpha_{ji}^k \left(\hat{\delta}_j^k \hat{p}_j^k\right)^{1-\sigma}\right]^{1/(1-\sigma)}; \tag{56}$$

equation (41) that defines bilateral imports,

$$\hat{X}_{ji}^k = \left(\hat{\delta}_j^k \hat{p}_j^k/\hat{P}_i^k\right)^{1-\sigma} \hat{X}_i^k; \tag{57}$$

and equation (43) that defines the representative agents' budget constraint and where the tax revenues now appear as a lump sum transfer,

$$E_i \hat{E}_i = A_i^0 N_i + \sum_{k\in\mathcal{K}^c} R_i^k \hat{r}_i^k \hat{Q}_i^k + \sum_{k\in\mathcal{K}^a, j\in\mathcal{I}, j\neq i} \left(\hat{\delta}_i^k - 1\right) \frac{X_{ij}^k \hat{X}_{ij}^k}{\hat{\delta}_i^k}. \tag{58}$$

Another approach to restrict trade adjustments is to fix the bilateral import shares to their initial values. Given the model Armington structure, fixing the bilateral trade shares is symmetric to what is done for land by fixing the acreage shares. This is done by simply replacing equation (41) with $\hat{X}_{ji}^k = \hat{X}_i^k$.

The welfare results when trade adjustments are limited are presented in columns 7 and 8 of table 4. The two constraints lead to very different welfare results, with much larger welfare losses in column 7, where bilateral import shares are fixed to their initial values, than in column 8, where welfare results are much closer to the benchmark results. This difference suggests that fixing the bilateral import shares is a stronger constraint on international trade than fixing the share of total exports and therefore a more appropriate counterfactual. We postpone the detailed comparison of the two approaches to section 6.3. Until this comparison, we present both measures of the role of trade for comparison with CDS, but we privilege the scenario that fixes the bilateral import shares for comparison with the role of acreage changes. The role of trade adjustments in adaptation to climate change, as measured in column 7, is smaller than the role of acreage adjustments but also much more heterogeneous. For example, trade adjustments play a much bigger role for Sub-Saharan Africa than acreage adjustments.

5.4 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 the average global change in potential yields to each field. 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

$$A_i^{fk\prime} = \hat{A} A_i^{fk}. \tag{59}$$

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 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 (59) is multiplicative in the initial yields, it cannot account for pairs 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 in fields has a huge impact. Climate change will reduce the productivity in many fields but will also make new production possible, reducing global welfare losses by one quarter.

To save on space, welfare results are reported for regional aggregates (defined in table A1). The amount of change in acreages and in trade flows is 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:

$$\text{MAD of acreage shares} = \frac{\sum_{i\in\mathcal{I}, f\in\mathcal{F}_i, k\in\mathcal{K}^c} s_i^f \pi_i^{fk} \left|\hat{\pi}_i^{fk} - 1\right|}{\sum_{i\in\mathcal{I}, f\in\mathcal{F}_i, k\in\mathcal{K}^c} s_i^f \pi_i^{fk}}. \tag{60}$$

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	−0.92	−0.87	−4.39	−6.93	−6.33	−3.09
Commonwealth of Independent States	−0.04	0.29	−3.34	0.02	0.11	−0.11
Europe	−0.27	−0.47	−3.39	−3.21	−2.95	−1.35
Latin America	1.11	0.36	6.22	4.76	4.47	1.39
Middle East and North Africa	−1.58	−2.91	−10.77	−12.92	−11.96	−5.78
Northern America	0.31	0.46	0.92	1.26	1.17	0.39
Oceania	0.88	1.19	3.29	4.27	4.00	1.64
Sub-Saharan Africa	−1.11	−8.48	−18.95	−30.13	−29.43	−21.24
World	−0.25	−0.52	−2.40	−3.30	−3.05	−1.72
World - No acreage shares adjustment	−0.28	−0.57	−2.64	−3.66	−3.71	−3.71
World - No bilateral import shares adjustment	−0.26	−0.76	−2.56	−4.49	−4.53	−3.02
World - No export shares adjustment	−0.26	−0.61	−2.50	−3.71	−3.45	−2.18
MAD of acreage shares	26.09	31.05	37.04	39.62	60.34	63.35
MAD of between-country acreage shares	25.06	29.98	35.77	38.30	33.58	41.04
MAD of international trade volumes	16.05	50.46	49.55	68.45	69.06	104.80

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

$$\text{MAD of between-country acreage shares} = \frac{\sum_{i\in\mathcal{I},k\in\mathcal{K}^c}\left(\sum_{f\in\mathcal{F}_i} s_i^f \pi_i^{fk}\right)\left|\hat{\pi}_i^k - 1\right|}{\sum_{i\in\mathcal{I},f\in\mathcal{F}_i,k\in\mathcal{K}^c} s_i^f \pi_i^{fk}}, \tag{61}$$

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:

$$\text{MAD of international trade volumes} = \frac{\sum_{i,j\in\mathcal{I},i\neq j,k\in\mathcal{K}^c} X_{ji}^k \left|\hat{X}_{ji}^k/\hat{p}_j^k - 1\right|}{\sum_{i,j\in\mathcal{I},i\neq j,k\in\mathcal{K}^c} X_{ji}^k}. \tag{62}$$

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 the shock is 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 the Middle East, North Africa, and Sub-Saharan Africa, while results are weakly changed for Northern and Latin America. 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 change than in other scenarios. In this scenario, there is almost no role for acreage or trade adjustments: welfare losses are almost the same whether these margins are active or not, which is consistent with the fact that this aggregate shock creates little change in relative prices and so little change in acreage and trade.

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 (39), the change in consumer prices is a power mean of import prices weighted by initial trade shares. If the initial trade shares (excluding trade to self) are small, the consumer price is very dependent on the domestic producer price, which increases sharply in the case of adverse shock if there are no exports to reduce. Sub-Saharan Africa is both exposed to a larger shock than the mean and is less connected through international trade so less able to adapt to the shock, which aggravates the mean effect. In this setting, there is heterogeneity within a country between crops and fields, so acreage adjustments do not matter, but trade adjustments do.

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 slightly fewer 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 tend to create more welfare losses than others because of the lack of adaptation through trade.

Column 4 of table 5 reports the results when the average country-crop shock is applied for each couple field-crop. This shock is closer to the benchmark climate change shock than either of the three previous scenarios. This shock is also similar to what would be obtained with a model with one field per country (and so to the early literature on the topic), since it neglects all within-country changes. In this case, comparative advantages change between countries and for all crops, but without within-country differentiation, outside of the initial field heterogeneity. This is the scenario with the highest global welfare loss, higher even than in the benchmark without new crops. Comparing the last rows of columns 4 and 5 shows that having shocks that are heterogeneous within countries affects the amount of change in international trade volumes little, consistent with the idea that countries should have the same comparative advantages between the two columns. In column 5, more adjustments take place on the supply side, with much more change 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 place mostly between countries, with negligible within-country adjustments, and the role of acreage adjustments is small. With within-country shock heterogeneity (columns 5–6), the share of within-country adjustments increases to close to one-third. Common to all the scenarios without within-country heterogeneity is the fact that they neglect the possibility of planting new crops on fields. For a better comparison with the benchmark, the benchmark simulation without this possibility of planting new crops is presented in column 5 and shows a crucial result. Preventing new crops from being planted increases the welfare losses of climate change by 77% with respect to the benchmark. Going one step further and preventing all acreage adjustment increases the losses further but by less than preventing new crops. This shows that the most important part of the supply-side adaptation to climate change is the possibility of planting crops that could not grow before climate change. Adjusting the acreages within the set of crops that can be grown initially has a much smaller effect.

6 Sensitivity to the behavioral assumptions

In this section, we analyze how our behavioral assumptions affect our conclusions about the respective role of acreage and trade adjustments. We do this by varying the flexibility of each adjustment margin, which clarifies the inner workings of the model and the mechanisms that trigger more or less role of a role for international trade adjustments. We also parameterize the model with local behaviors as close as possible to those used in CDS to clarify what drives the differences between our conclusions. The various models are presented in table 6. For comparison, the last row displays CDS' benchmark results.

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 in model 3, a value that could be found in poor populations as discussed in section 4.1, and in model 4 we consider an elasticity of 1

Table 6: Role of each adjustment margins in welfare changes (as % of world GDP)

		No adjustment on		
Model	Full adjustment (1)	acreage shares (2)	bilateral import shares (3)	export shares (4)
1. Benchmark calibration ($\epsilon = 0.2, \kappa = 0.6, \varsigma = 0.9, \theta = 1.1, \eta = 0, \sigma = 5.4$)	−1.72	−3.71	−3.02	−2.18
2. Benchmark calibration – 5-arcminute modeling	−1.58	−4.30	−2.82	−2.01
3. $\epsilon = 0.5$	−1.00	−1.59	−1.30	−1.09
4. $\epsilon = 1$	−0.74	−1.12	−0.89	−0.78
5. $\kappa = 0.4$	−3.98	−11.88	−8.59	−5.44
6. $\kappa = 1.2$	−0.67	−1.22	−1.14	−0.77
7. $\kappa = 2.82$	−0.32	−0.58	−0.49	−0.36
8. $\varsigma = 0.6$	−1.82	−3.90	−3.60	−2.31
9. $\varsigma = 1.8$	−1.58	−3.45	−2.98	−1.99
10. $\varsigma = 2.82$	−1.50	−3.31	−2.82	−1.90
11. $\theta = 1.05$	−1.85	−3.67	−3.54	−2.33
12. $\theta = 1.2$	−1.53	−3.80	−2.75	−1.92
13. $\eta = 0.02$	−1.49	−2.91	−2.43	−1.82
14. $\eta = 0.04$	−1.31	−2.40	−2.03	−1.57
15. $\eta = 0.06$	−1.18	−2.05	−1.75	−1.39
16. $\sigma = 10$	−1.32	−3.12	−2.62	−1.82
17. $\kappa = \varsigma = 2.82$	−0.27	−0.48	−0.40	−0.30
18. $\epsilon = 1, \kappa = \varsigma = 2.82$	−0.21	−0.31	−0.25	−0.22
19. $\theta = 1.2407$	−1.47	−3.83	−2.65	−1.84
20. $\epsilon = 1, \kappa = \varsigma = 2.82, \theta = 1.2407$	−0.20	−0.32	−0.23	−0.20
21. $\epsilon = 1, \kappa = \varsigma = 2.82, \theta = 1.2407$ – 5-arcminute modeling	−0.19	−0.35	−0.22	−0.20
Costinot et al. (2016) benchmark results	−0.26	−0.78	–	−0.27

Notes: ϵ is the price elasticity of demand for the bundle of agricultural goods, κ is elasticity of substitution between agricultural products for final demand, ς is the elasticity of substitution between agricultural products for feed demand, θ is shape parameter of the Fréchet distribution used for crop yields, η is the elasticity of crop output to the input of the non-agricultural good, and σ is the elasticity of substitution between varieties.

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.

Welfare losses decrease with a more elastic demand. However, these changes in welfare results are not straightforward to interpret, as expected when preferences and behaviors are changed simultaneously. With a more elastic demand, the contribution of changes in acreages decreases. Instead of a doubling of the global welfare losses in the benchmark, losses increase by 51% if $\epsilon = 1$. The effect is similar if considering the counterfactual where bilateral import shares are fixed: the role of import shares in adaptation to climate change decreases, but the contribution of import shares to adaptation relative to the contribution of acreage adjustments stays the same. This result proceeds from a simple intuition: a more elastic demand reduces the size of the price adjustments, so it reduces the adaptive role of the supply and trade margins that are triggered by changes in relative prices. This intuition holds for the other demand parameters analyzed below: these parameters matter a lot for the size of the welfare results but reduce the role supply and trade adjustments similarly.

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 therefore 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 just 3 to 5%. This slow adjustment is in the context of poor Indian households that could be expected to have higher food demand elasticities, and thus 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 a scenario with an elasticity of substitution of 1.2 in model 6, the double of the benchmark value. We also report the results with an elasticity lower than benchmark (model 5) and with the elasticity used in CDS: 2.82 (model 7). This substitution elasticity plays a key role in determining the size of the welfare losses with an order of magnitude between the smallest and the highest losses. Climate change is much less costly with more substitution between food products, since not all food products are affected alike and some even show higher potential yields under climate change, allowing the consumption to reallocate to cheaper products. However, this parameter influences the respective role of changes in acreage and in trade little.

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 a lower bound in the sensitivity analysis. For the upper bound, we consider the double of the benchmark elasticity, which would put the feed demand elasticities in the high end of the literature. We also consider the substitution elasticity used for final demand in CDS: 2.82. Models 8–10 of table 6 report the results for these alternative values. As expected, a more elastic demand for feed implies less welfare loss. However, this effect is much lower than for final demand, despite a large share of 31% of feed demand in total demand for crops. This lower effect stems from the fact that the demand for feed is concentrated into far fewer crops than the demand for food (e.g., in the U.S., grass, maize, and soybean represent 80% of feed demand), which greatly decreases the opportunity for substitution. The respective role of production and trade adjustments are not affected by the choice of this parameter.

6.2 Supply

Acreage choice We vary the acreage elasticity around its benchmark value, halving and doubling it. Since the acreage elasticity is proportional to $\theta - 1$, halving it decreases θ to 1.05 and doubling it increases 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 θ. When the value of θ is changed, the calibration of the initial rents should be done for the new value according to equation (44). The aggregate values of production, trade, and final demand stay the same, but a different θ implies slightly different initial land rents and thus different field acreages.

Models 11 and 12 of table 6 report the results of this exercise. Varying the degree of within-field heterogeneity from 1.05 to 1.2 influences welfare changes, with lower aggregate losses for a higher θ. Despite the large variations that it implies in the supply elasticities, the welfare changes remain modest compared to the fact that welfare losses more than double if acreage shares are forced to stay the same. This is explained by what was discussed in section 5.4: the largest contribution to production adjustments comes from the possibility of planting new crops on fields, which is not affected by θ. Despite limited welfare effects, θ affects the respective role of acreage and trade adjustments. With $\theta = 1.2$, there are more acreage adjustments in the full adjustment setup, which decreases the welfare losses and increase the contribution of acreage adjustments. The balance between acreage and trade adjustments is also affected: with a lower

θ, their contribution is almost identical, while with a higher θ, acreage adjustments contribute much more to adaptation, although the contribution of trade adjustments remains substantial. This points to some substitution between these two margins of adjustment: if one is more flexible, it decreases the need for the other. The less flexible domestic supply is, the wider the imbalances between domestic supply and demand are, which would call for more international trade to reduce the imbalances.

Yield elasticity For the sake of parsimony and because of the difficulty of obtaining 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 increasing inputs used for crop production profitable. Such a reaction is likely to be heterogeneous across fields, countries, and crops, depending on the existing gaps with respect to maximum yields, among other things. 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 for all crops and all countries. Appendix F 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, since more elastic yields imply less land-use changes and consequentially less carbon emissions from planting crops on new lands. Berry (2011) and Berry and Schlenker (2011) argue that GTAP-based models use too large of 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 also being the high value used in GTAP models and criticized by Berry (2011). Models 13-15 of table 6 report 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 $\eta = 0.06$, model 15 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 and the potential adaptive role of acreage and trade adjustments without affecting their relative contribution.

Degree of spatial aggregation Data on potential yields are available at the 5-arcminute level, the level at which CDS model is built. In this paper for reducing the computational burden of solving the model, we have aggregated the potential yields information to the 1-degree level. This significantly reduces the number of fields to account for, but it also reduces the spatial heterogeneity and the corresponding possibility to reallocate crops between fields. It is important to verify that this assumption is not behind the results that trade matters for adaption by decreasing the supply-side adaptation margin. One hint that the spatial aggregation may bias the results is provided in column 4 of table 5. In the limit, if fields are aggregated to one per country and all within-country heterogeneity is neglected, the role of acreage adjustments decreases grealy, becoming inferior to the role of trade adjustments.

To verify the role of this specification, we solve the model at the 5-arcminute level for two calibrations: the benchmark calibration and the closest calibration to CDS (see section 6.4 for details). The results are available in models 2 and 20 and can be compared to models 1 and 19 that have the same calibrations. For CDS calibration, the difference is very small, but for the benchmark calibration, keeping as much spatial detail as possible matters. With more spatial heterogeneity, there are more supply-side adjustments, which decreases welfare losses and increases the role of acreage changes. The role of trade adjustments also decreases but remains sizable. From this exercise, we can conclude that a setting with more detailed spatial information is important to capture the extent of supply-side adjustments better. However, for the purpose of this paper, yields are sufficiently spatially correlated that an aggregation at the 1-degree level is unlikely to reverse the paper's conclusions.

6.3 International trade

To better understand the role of trade adjustments, we consider two alternative models. First, we consider a model with a higher Armington elasticity of 10, the value estimated in Caliendo and Parro (2015) for agricultural products. Second, we consider a situation of integrated world markets, 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. This situation reflects the reality that 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 the changes to be made to have integrated world markets in the model below.

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 (40) and producer prices (42) are collapsed and summed over all countries. 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 thus some production) being zero under climate change but positive in the baseline. This is done by expressing equation (32) for crops as a complementarity slackness condition:

$$\hat{r}_i^k \geq 0 \perp \hat{r}_i^k \geq \left(\hat{p}^k - \phi_i^{k,\text{labor}}\right) / \phi_i^{k,\text{land}}. \tag{63}$$

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 (63), the model with integrated world markets is solved numerically as a mixed complementarity problem using the solver PATH.

Model 16 of table 6 reports the results with a higher Armington elasticity. With more elastic trade, there are more trade reallocations under full adjustments and lower welfare losses. The adaptive roles of acreage and trade decline accordingly without changes in their respective role. However, the interpretation of this result is not trivial, given that changing the trade elasticity also involves changing the preferences for varieties. For the integrated world markets, we report only the results under full adjustment in column 1 of table 7. If all markets except grass are integrated, global welfare losses are reduced by one third, falling from 1.72% to 0.57%. The reduction is especially strong for Sub-Saharan Africa, which suffers a 0.63% welfare loss instead of a 21.24% loss. This demonstrates that one of the main reasons for 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 welfare gains in the benchmark because of terms-of-trade gains in agricultural products, is barely affected in welfare terms under integrated world markets by climate change as agricultural prices and the associated terms of trade evolve much less.

We would like now to compare the two counterfactuals with restrictions on trade. In all model variations, the counterfactual exercise proposed by CDS where export shares are fixed using trade taxes leads to more moderate welfare

Table 7: Effects of the assumptions about international trade (percentage change)

Variable	Integrated world markets (1)	$\sigma = 10$ (2)	Benchmark $\sigma = 5.4$ (3)	Fixed export shares (4)	Fixed bilateral import shares (5)
Welfare change					
Asia	−0.98	−2.30	−3.09	−4.18	−4.93
Commonwealth of Independent States	−0.33	−0.16	−0.11	0.34	−1.31
Europe	−0.77	−1.11	−1.35	−1.42	−2.37
Latin America	0.46	0.87	1.39	2.04	4.14
Middle East and North Africa	−2.19	−4.48	−5.78	−8.54	−9.43
Northern America	−0.00	0.28	0.39	0.79	0.36
Oceania	0.45	1.14	1.64	2.82	2.70
Sub-Saharan Africa	−0.63	−14.89	−21.24	−29.60	−46.58
World	−0.57	−1.32	−1.72	−2.18	−3.02
Agricultural good consumption	−7.59	−13.96	−16.66	−19.41	−21.43
Agricultural good price	49.87	133.40	187.13	275.49	506.68
MAD of acreage shares	69.42	63.79	63.35	64.17	62.95
MAD of between-country acreage shares	51.99	42.16	41.04	41.22	39.68
MAD of international trade volumes		120.07	104.80	73.71	60.40

losses than the restriction we have adopted, which fixes the bilateral import shares. In the case of the benchmark calibration, we can compare the restrictions' effects in columns 4 and 5 of table 7. Since both counterfactuals restrict trade adjustments, 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, with a smaller effect for fixed export shares. However, in contrast with the counterfactual on acreage that blocks all acreage changes, the counterfactuals on trade do not block all trade adjustments. We measure how much they restrict trade changes through the MAD of international trade volumes. The MAD of international trade volumes is 105% in the benchmark simulation. It decreases to 74% if export shares are fixed and 60% if bilateral export shares are fixed. We draw two conclusions from this observation. Firstly, fixing bilateral import shares maintains trade flows closer to their initial values than fixing export shares. It is a stronger constraint, and therefore a more legitimate way to measure the role of trade in climate change adaptation. Secondly, despite the strong restrictions imposed on trade, the MAD of international trade volumes are large at 60%, showing that a lot of trade adjustments still take place even if the bilateral import shares have been fixed. This counterfactual delivers what should be considered a lower bound of the contribution of trade to climate change adaptation. In our simulations, the role of acreage changes is always more important than the one of trade changes, but we must keep in mind that one is a measure where all adjustments have been prevented while the other has only prevented 60% of the adjustments. Given the proximity of the two measures, it is not unreasonable to think that the role of trade in climate change adaptation is as large or larger than the role of acreage changes.

6.4 Costinot et al. (2016) calibration

To understand better the differences between CDS' results and ours, we have also simulated our model using their behavioral assumptions, mostly combining parameter values previously tested. On the demand side, it suffices to assume higher elasticities: a unitary demand elasticity for the food bundle and a substitution elasticity equal to 2.82 for final demand and demand for feed. Regarding the supply-side, and so the degree of within-field heterogeneity, θ, even if this parameter has the same interpretation in their model and ours, it does not have the same quantitative effect. To make the two models comparable, we select θ to target their aggregate supply elasticity. From equation (8) in CDS, their supply elasticities can be derived:

$$\frac{\partial \ln Q_i^k}{\partial \ln p_i^k} = (\theta-1)\sum_{f\in\mathcal{F}_i}\left(1-\pi_i^{fk}\right)\frac{Q_i^{fk}}{Q_i^k} = (\theta-1)\sum_{f\in\mathcal{F}_i}\left(\underbrace{1-\sum_k \pi_i^{fk}}_{\text{Extensive}} + \underbrace{\sum_k \pi_i^{fk} - \pi_i^{fk}}_{\text{Intensive}}\right)\frac{Q_i^{fk}}{Q_i^k}. \tag{64}$$

This expression differs from equation (26) by the ratio of the producer price to the land rents, p_i^k/r_i^k, because our model allocates land according to the land rents, not according to the producer price. From their programs, we can calculate an average world acreage elasticity, weighted by the value of production, equal to 1.39. To reproduce the same average elasticity for the same set of crops in our model requires $\theta = 1.2407$, well below their value of 2.46, in part because of the role of p_i^k/r_i^k. Since supply elasticities are proportional to $\theta - 1$, increasing θ from 1.1 to 1.2407 amounts to more than double the elasticities from our benchmark.

Models 17–21 of table 6 present calibrations using combinations of CDS behavioral assumptions. Assuming an elasticity of substitution of 2.82 for final demand and demand for feed in model 17 is enough to bring down the welfare losses to the order of magnitude in CDS. However, it does not change the respective role of production and trade adjustments. Adopting in addition the assumption of a unitary elasticity for the final demand (model 18) further reduces the losses and slightly reduces the role of trade. In model 19, where only CDS supply-side behavior is reproduced, the role of trade starts to decline significantly but remains sizable, despite more reallocation between crops. So, it is really the combination of very flexible demand and supply that reduces the role of trade so strongly (models 20 and 21). Indeed, despite large within-field reallocations in model 19, important trade adjustment are still required because the new production patterns do not necessarily match the local preferences. With more flexible preferences (a higher κ), this is no longer a problem, and local food demand adjusts to local production, reducing the need for trade adjustments.

To better understand the rest of the results, we must note that even when adopting CDS calibration, there are irreducible differences between the two models mostly related to the modeling of crop production. CDS assume that the climate change shock is a shock to the total factor productivity, while we follow to what agronomists can predict: the effect of climate change on yields, so on the partial productivity of land. Since, in GTAP data, land accounts for one-fifth of production costs on average, this assumption reduces the size of the shock by the same amount. On the other hand, we include many more crops in the model than they do. The subset of CDS crops represents just 38% of the production value of all our crops. After combining these two differences, we should expect a lower climate change shock in our model, which explains why welfare losses under full adjustments are lower when we adopt their behavioral assumptions (models 20 and 21) than in their benchmark (−0.26). Under the same behavioral assumptions, we can replicate CDS results that trade adjustments do not matter much (whatever the measure of trade adjustment one adopts). We also find that production adjustments matter, but a key difference with CDS is that production adjustments matter much less than in their model, where welfare losses triple without production adjustment, a result that can be achieved in our case only by assuming a smaller elasticity of substitution as in model 5.

There is one last difference between the two models that could explain this large difference in the role of production adjustments. CDS supply elasticity can be decomposed as in equation (64) between an extensive margin (the contribution to production of the extension over "unused" land) and an intensive margin (the substitution between crops for a given area of agricultural land). If we consider the same set of crops, our model also includes an extensive margin over the other crops, in particular grass. A key difference is that this extension has an opportunity cost in our case because the land has an alternative valuable use. In CDS, the "unused" land on which crops can expand has no opportunity cost. So, there is a factor supply of land only restricted by the availability of land and the labor cost to put land into production. Even if calibrated to have the same local behavior, the two models differ a lot; in our case, production adjustments only come from reallocation between crops, while in CDS, they mostly come from adjustments to total agricultural areas (decomposing the supply elasticities shows that the extensive margin is the principal component).

To summarize, CDS finding that trade adjustments matter little to adaptation to climate change while production adjustments account for most of the adaptation can be explained mostly by the following features of their model. Firstly, the combination of demand and supply schedules that are very flexible with respect to the crop relative prices—three times more than usual estimates—implies that acreages are very reactive to the new climatic and market conditions while local diets adjust to match this new production pattern. Secondly, using a situation where total export shares are maintained constant as counterfactual for measuring the role of trade minimizes the role of trade by imposing a small constraint on trade adjustments.

7 Conclusion

This paper estimates how climate change in the agricultural sector will affect the world economy, focusing on the role of production and trade adjustments as margins of adaptation. 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 2080 horizon is based on simulations from crop science. In our benchmark calibration, climate change reduces welfare globally by 1.72%, 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, allowing production to relocate where it is more profitable. The most important supply-side adaptation appears to be the ability to introduce crops that were not productive before climate change to a field, a feature made possible by the functional forms used in our spatially explicit modeling. Since these adjustments reallocate crop production between countries, as well as within countries, international trade plays a strong role in balancing the new domestic supply and demand schedules. If the trade adjustments are prevented from occurring by forcing bilateral import shares to stay constant, welfare losses increase by 76%. This result is in contrast with Costinot et al.'s (2016) result that only production adjustments matter in adaptation to climate change while trade adjustments would barely reduce welfare losses. The key difference between our models is in demand and supply elasticities. Our elasticities are taken from the literature, which consistently finds that food demand and supply are inelastic, while Costinot et al. estimate these elasticities in cross-section despite the loose mapping existing between their model and the available data (e.g., a lot of the between-country differences in agricultural good consumption can be explained by income effects, biofuel policies, and trade policies that are neglected in their model and estimation).

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, farm-level decisions regarding planting decisions and adjusting 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, which 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 root of the issue—climate change agreement—and the resilience of existing trading institutions, political pressure to use trade policy instruments to mitigate the terms-of-trade impact of agricultural productivity shock may in fact 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 reducing 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. At the same time, the Armington assumption of imperfect substitutability between the same crop from two different countries may prevent the emergence of trade patterns that are much different structurally from current patterns. 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 (44) 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:

$$\begin{aligned} \frac{\partial h_i^k\left(\rho_i\right)}{\partial \rho_i^l} &= \frac{\theta-1}{\theta} \left(\frac{1}{\exp h_i^k\left(\rho_i\right)}\right) \left(R_i^k\right)^{-1} \sum_{f \in \mathcal{F}_i} s_i^f \left(A_i^{fk}\right)^\theta \mathrm{e}^{-\rho_i^l} \left(A_i^{fl}\right)^\theta \left[\sum_{l' \in \mathcal{K}^c} \mathrm{e}^{-\rho_i^{l'}} \left(A_i^{fl'}\right)^\theta\right]^{1/\theta-2}, && \text{(A2)} \\ &= \frac{\theta-1}{\theta} \left(\frac{1}{\exp h_i^k\left(\rho_i\right)}\right) \left(R_i^k\right)^{-1} \sum_{f \in \mathcal{F}_i} s_i^f \left(A_i^{fk}\right)^\theta \pi_i^{fl} \left[\sum_{l' \in \mathcal{K}^c} \mathrm{e}^{-\rho_i^{l'}} \left(A_i^{fl'}\right)^\theta\right]^{(1-\theta)/\theta}. && \text{(A3)} \end{aligned}$$

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 $\tilde{\rho}_i = t_i \rho_{i,0} + \left(1 - t_i\right) \rho_{i,1}$ 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

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

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 (44). □

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 (20) and (24):

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

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

and to a slightly different calibration for the land rents, where equation (44) 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 decomposition

From the definition of the equivalent variation and equation (45), we have:

$$\mathrm{d}\, EV_i = \frac{\partial e\left(P_i^0, P_i, U_i\right)}{\partial U_i} \mathrm{d}\, U_i = P_i^0 U_i \,\mathrm{d} \ln U_i. \tag{A11}$$

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

$$\mathrm{d}\, E_i = \frac{\partial e\left(P_i^0, P_i, U_i\right)}{\partial P_i} \mathrm{d}\, P_i + \frac{\partial e\left(P_i^0, P_i, U_i\right)}{\partial U_i} \mathrm{d}\, U_i, \tag{A12}$$

$$= C_i \,\mathrm{d}\, P_i + \mathrm{d}\, EV_i, \tag{A13}$$

and so

$$\mathrm{d}\, EV_i = E_i \,\mathrm{d} \ln E_i - P_i C_i \,\mathrm{d} \ln P_i. \tag{A14}$$

From now on, we assume no trade deficits, so from equation (31):

$$E_i \,\mathrm{d} \ln E_i = \sum_{k \in \mathcal{K}^c} R_i^k \,\mathrm{d} \ln R_i^k. \tag{A15}$$

Land rents can be further decomposed using equation (25), for $k \in \mathcal{K}^c$:

$$\mathrm{d}\ln R_i^k = \mathrm{d}\ln r_i^k + \mathrm{d}\ln Q_i^k. \tag{A16}$$

From equations (20) and (24) and using $\mathrm{d}\ln A_i^{fk}(\omega) = \mathrm{d}\ln A_i^{fk}$, we get for $\mathrm{d}\ln Q_i^k$:

$$\mathrm{d}\ln Q_i^k = \sum_{f\in\mathcal{K}_i} \frac{Q_i^{fk}}{Q_i^k}\left[\mathrm{d}\ln A_i^{fk} + (\theta-1)\left(\mathrm{d}\ln r_i^k + \mathrm{d}\ln A_i^{fk}\right) - \sum_{l\in\mathcal{K}^c}(\theta-1)\,\pi_i^{fl}\left(\mathrm{d}\ln r_i^l + \mathrm{d}\ln A_i^{fl}\right)\right]. \tag{A17}$$

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

$$\begin{aligned}\sum_{k\in\mathcal{K}^c} R_i^k\,\mathrm{d}\ln R_i^k &= \sum_{f\in\mathcal{F}_i,k\in\mathcal{K}^c} r_i^k Q_i^{fk}\left[\theta\left(\mathrm{d}\ln r_i^k + \mathrm{d}\ln A_i^{fk}\right) - \sum_{l\in\mathcal{K}^c}(\theta-1)\,\pi_i^{fl}\left(\mathrm{d}\ln r_i^l + \mathrm{d}\ln A_i^{fl}\right)\right],\\ &= \sum_{f\in\mathcal{F}_i,k\in\mathcal{K}^c}\left(\mathrm{d}\ln r_i^k + \mathrm{d}\ln A_i^{fk}\right)\left[\theta r_i^k Q_i^{fk} - (\theta-1)\,\pi_i^{fk}\sum_{l\in\mathcal{K}^c} r_i^l Q_i^{fl}\right].\end{aligned} \tag{A18}$$

Combining equations (20) and (24), 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 (A18) in

$$\sum_{k\in\mathcal{K}^c} R_i^k\,\mathrm{d}\ln R_i^k = \sum_{f\in\mathcal{F}_i,k\in\mathcal{K}^c} r_i^k Q_i^{fk}\left(\mathrm{d}\ln r_i^k + \mathrm{d}\ln A_i^{fk}\right). \tag{A19}$$

Now from labor market clearing we have:

$$w_i N_i = \sum_{k\in\mathcal{K}} w_i N_i^k = \sum_{k\in\mathcal{K}} \phi_i^{k,\text{labor}}\left(\sum_{j\in\mathcal{I}} X_{ij}^k\right). \tag{A20}$$

Multiplying equation (A20) by $\mathrm{d}\ln w_i = 0$ and using (32), we get

$$0 = w_i N_i\,\mathrm{d}\ln w_i = \sum_{k\in\mathcal{K}}\left(\sum_{j\in\mathcal{I}} X_{ij}^k\right)\left(\mathrm{d}\ln p_i^k - \phi_i^{k,\text{land}}\,\mathrm{d}\ln r_i^k - \phi_i^{k,\text{feed}}\,\mathrm{d}\ln P_i^{k,\text{feed}}\right). \tag{A21}$$

Then, we can decompose final consumption:

$$\begin{aligned}P_i C_i\,\mathrm{d}\ln P_i &= P_i C_i\left(\sum_{k\in\mathcal{K}^a,j\in\mathcal{I}} \alpha_i^k \alpha_{ji}^k\,\mathrm{d}\ln p_j^k\right),\\ &= \sum_{k\in\mathcal{K}^a,j\in\mathcal{I}}\left(X_i^k - P_i^k x_i^k\right)\alpha_{ji}^k\,\mathrm{d}\ln p_j^k.\end{aligned} \tag{A22}$$

Finally, from equation (A14), we combine equations (A19), (A21), and (A22). 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 (47).

D Data sources and description

D.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 gridded information at the 5-arcminute level about land resources, climate, land cover, potential yields, and other statistics for 49 crops publicly available. 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, 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 a 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 scenarios 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).

In our model, we use 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 E provides details about the aggregation procedure and the underlying theoretical assumptions. To put it 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 a 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 conversions of 1 ton of cane to 0.095 ton of sugar and 1 ton of beet to 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 instead use 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 result in very large price movements, which makes 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 detailed level compared to a more aggregated level. Little information is lost with aggregation, but there are high costs in the size of the resulting model if the 5-arcminute level is used. 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 A1 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 (47): $\hat{A}_i^f = \sum_{k\in\mathcal{K}^c} r_i^k Q_i^{fk} \hat{A}_i^{fk} / \sum_{k\in\mathcal{K}^c} r_i^k Q_i^{fk}$. This approach allows the aggregate first-order effect of climate change on yields to be visualized. However, being based on a first-order approach, it neglects the fact that the loss of productivity of a 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 gains. The tropics would be the most affected regions, with very strong reductions in current yields. The Northern middle latitudes would be in between, with relative changes closer to 0 and some regions, often mountainous regions like the Alps or the Himalayas, even displaying gains.

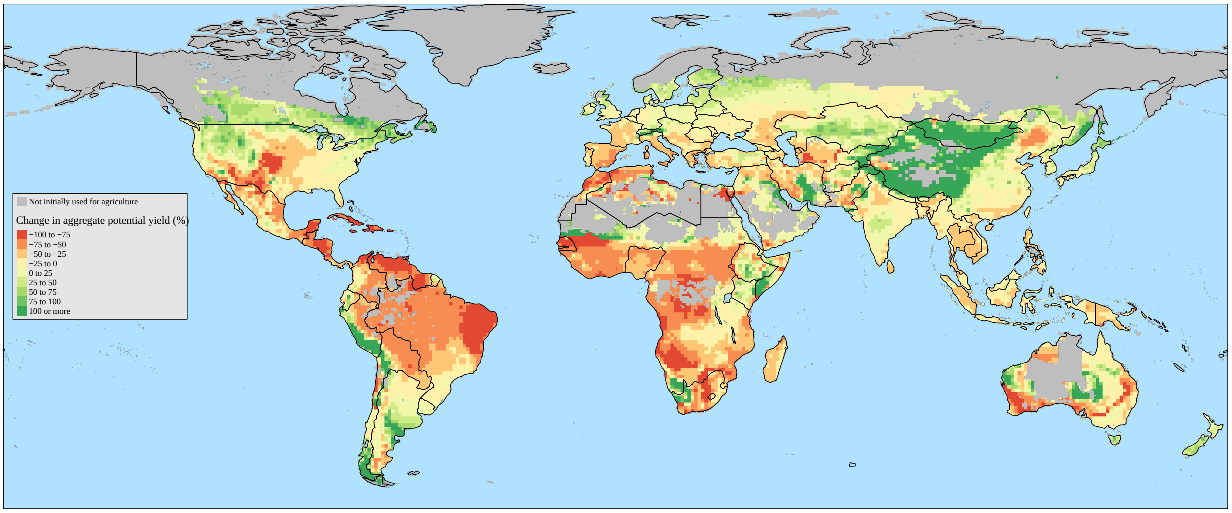

Figure A1: Relative changes in aggregate potential yields. Gray areas indicate areas not used for agriculture in 2007.

D.2 Spatial extent of agricultural land

The model requires information about the share of the cells used for agriculture for two purposes. First, it is used to weight the GAEZ potential yields when they are aggregated at a coarser spatial level. Second, it is used so the model avoids 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 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 on a country is 12 for the Netherlands and the highest is 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 large uncertainties in global land cover data (Fritz et al., 2011).

D.3 Agricultural production, final demand, feed demand, and trade

Most of the other agricultural data used in the model comes 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 and is 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 at farm gate 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 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 in tons. 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 by 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 the value of domestic trade from the value of production and exports: $X_{ii}^k = p_i^k Q_i^k - \sum_{j \in \mathcal{I}, j \neq i} X_{ij}^k$.

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

D.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 we remove 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 counted as intermediate consumption in the input-output matrix.

Non-agricultural value added, corresponding to $w_i N_i^0$ in the model, is calculated as a residual to target the countries’ GDP. Similarly, bilateral trade in the non-agricultural good is 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. Then trade imbalances as present in the world in 2011 are removed, and the resulting equilibrium allows us to calibrate the model on an initial equilibrium.

E Crop aggregation

Here, we show under which conditions and how crops can be aggregated together. We 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 include the crops that have been aggregated by $\tilde{\mathcal{K}}^c$.

Given equation (20), for the aggregate crop to use the same share of land in each field as the sum of the individual crops, we need

$$\sum_{k \in \mathcal{K}^\kappa} \frac{\left(r_i^k A_i^{fk}\right)^\theta}{\sum_{l \in \mathcal{K}^c} \left(r_i^l A_i^{fl}\right)^\theta} = \frac{\left(r_i^\kappa A_i^{f\kappa}\right)^\theta}{\sum_{l \in \tilde{\mathcal{K}}^c} \left(r_i^l A_i^{fl}\right)^\theta}, \tag{A23}$$

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

$$\sum_{l \in \mathcal{K}^c} \left(r_i^l A_i^{fl}\right)^\theta = \sum_{l \in \tilde{\mathcal{K}}^c} \left(r_i^l A_i^{fl}\right)^\theta, \tag{A24}$$

which together with equation (A23) implies

$$\sum_{k \in \mathcal{K}^\kappa} \left(r_i^k A_i^{fk}\right)^\theta = \left(r_i^\kappa A_i^{f\kappa}\right)^\theta, \tag{A25}$$

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

$$A_i^{f\kappa} = \frac{\left[\sum_{k \in \mathcal{K}^\kappa} \left(r_i^k A_i^{fk}\right)^\theta\right]^{1/\theta}}{r_i^\kappa}. \tag{A26}$$

The equality of field-level production implies from (23)

$$\sum_{k\in\mathcal{K}^\kappa} A_i^{fk}\left(r_i^k A_i^{fk}\right)^{\theta-1} = A_i^{f\kappa}\left(r_i^\kappa A_i^{f\kappa}\right)^{\theta-1}, \tag{A27}$$

Equations (A26) and (A27) 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

$$A_i^{f\kappa} = \left[\sum_{k\in\mathcal{K}^\kappa}\left(A_i^{fk}\right)^\theta\right]^{1/\theta}. \tag{A28}$$

F Elastic yields

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

$$Q_i^{fk}(\omega) = \min\left[A_i^{fk}(\omega)\left(I_i^{fk}(\omega)/\bar{I}_i^{fk}\right)^\eta, N_i^{fk}(\omega)/\nu_i^k\right], \tag{A29}$$

where $I_i^{fk}(\omega)$ is the level of (fertilizer) inputs of the non-agricultural good and $0 \le \eta < 1 - 1/\theta$ 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

$$Q_i^{fk}(\omega) = A_i^{fk}(\omega)\left(I_i^{fk}(\omega)/\bar{I}_i^{fk}\right)^\eta = N_i^{fk}(\omega)/\nu_i^k. \tag{A30}$$

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:

$$R_i^{fk}(\omega) = p_i^k Q_i^{fk}(\omega) - w_i N_i^{fk}(\omega) - P_i^0 I_i^{fk}(\omega). \tag{A31}$$

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

$$I_i^{fk}(\omega) = \eta\frac{p_i^k - w_i\nu_i^k}{P_i^0} Q_i^{fk}(\omega). \tag{A32}$$

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:

$$Q_i^{fk}(\omega) = \left(A_i^{fk}(\omega)\right)^{1/(1-\eta)}\left(\eta\frac{p_i^k - w_i\nu_i^k}{\bar{I}_i^{fk}P_i^0}\right)^{\eta/(1-\eta)}, \tag{A33}$$

from which we can derive the land rents:

$$R_i^{fk}(\omega) = \left(r_i^k A_i^{fk}(\omega)\right)^{1/(1-\eta)}\left(\bar{I}_i^{fk}P_i^0\right)^{\eta/(\eta-1)}(1-\eta)\,\eta^{\eta/(1-\eta)}. \tag{A34}$$

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

$$\pi_i^{fk} = \frac{\left[r_i^k A_i^{fk} \left(\bar{I}_i^{fk}\right)^{-\eta}\right]^\theta}{\sum_{l\in\mathcal{K}^c, r_i^l \geq 0} \left[r_i^l A_i^{fl} \left(\bar{I}_i^{fl}\right)^{-\eta}\right]^\theta}. \tag{A35}$$

The production at the field level is given by

$$Q_i^{fk} = s_i^f \pi_i^{fk} \operatorname{E}\left[A_i^{fk}(\omega) \left(I_i^{fk}(\omega)/\bar{I}_i^{fk}\right)^\eta | R_i^{fk}(\omega) \in \arg\max_{l\in\mathcal{K}^c} R_i^{fl}(\omega)\right], \tag{A36}$$

$$= s_i^f \pi_i^{fk} \left(\frac{\eta r_i^k}{\bar{I}_i^{fk} P_i^0}\right)^{\eta/(1-\eta)} \operatorname{E}\left[\left(A_i^{fk}(\omega)\right)^{1/(1-\eta)} | R_i^{fk}(\omega) \in \arg\max_{l\in\mathcal{K}^c} R_i^{fl}(\omega)\right]. \tag{A37}$$

From the standard properties of the Fréchet distribution we have

$$E\left[R_i^{fk}(\omega) | R_i^{fk}(\omega) \in \arg\max_{l\in\mathcal{K}^c} R_i^{fl}(\omega)\right] = \frac{\Gamma(1-1/(1-\eta)\theta)}{\Gamma(1-1/\theta)} \left(\eta P_i^0\right)^{\eta/(\eta-1)} (1-\eta) \left\{\sum_{l\in\mathcal{K}^c, r_i^l \geq 0} \left[r_i^l A_i^{fl} \left(\bar{I}_i^{fk}\right)^{-\eta}\right]^\theta\right\}^{1/(1-\eta)\theta}. \tag{A38}$$

So

$$E\left[\left(A_i^{fk}(\omega)\right)^{1/(1-\eta)} | R_i^{fk}(\omega) \in \arg\max_{l\in\mathcal{K}^c} R_i^{fl}(\omega)\right] = \frac{\Gamma(1-1/(1-\eta)\theta)}{\Gamma(1-1/\theta)} \left(A_i^{fk}\right)^{1/(1-\eta)} \left(\pi_i^{fk}\right)^{-1/(1-\eta)\theta}, \tag{A39}$$

and

$$Q_i^{fk} = s_i^f \left(\frac{\eta r_i^k}{\bar{I}_i^{fk} P_i^0}\right)^{\eta/(1-\eta)} \frac{\Gamma(1-1/(1-\eta)\theta)}{\Gamma(1-1/\theta)} \left(A_i^{fk}\right)^{1/(1-\eta)} \left(\pi_i^{fk}\right)^{1-1/(1-\eta)\theta}. \tag{A40}$$

From (A40), the elasticity of production to output price is

$$\frac{\partial \ln Q_i^k}{\partial \ln p_i^k} = \frac{p_i^k}{r_i^k}\left[\underbrace{\frac{\eta}{1-\eta}}_{\text{Yield}} + \underbrace{\frac{\theta(1-\eta)-1}{1-\eta} \sum_{f\in\mathcal{F}_i} \left(1-\pi_i^{fk}\right) \frac{Q_i^{fk}}{Q_i^k}}_{\text{Acreage}}\right]. \tag{A41}$$

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 (26). 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 input and the field-level land rents can be derived:

$$I_i^{fk} = \eta \frac{r_i^k}{P_i^0} Q_i^{fk}, \tag{A42}$$

$$R_i^{fk} = (1-\eta)\, r_i^k Q_i^{fk}. \tag{A43}$$

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 (32), (33), and (40) are now replaced by

$$\hat{p}_i^k = \left(\phi_i^{k,\text{land}} + \phi_i^{k,\text{inputs}}\right)\hat{r}_i^k + \phi_i^{k,\text{feed}}\hat{P}_i^{k,\text{feed}}, \tag{A44}$$

$$\hat{Q}_i^k = \left(\eta\frac{r_i^k\hat{r}_i^k}{\bar{I}_i^{fk}P_i^0}\right)^{\eta/(1-\eta)}\frac{\Gamma\left(1-1/(1-\eta)\,\theta\right)}{\Gamma\left(1-1/\theta\right)}\sum_{f\in\mathcal{F}_i}\frac{s_i^f\left(A_i^{fk\prime}\right)^{1/(1-\eta)}}{Q_i^k}\left\{\frac{\left[r_i^k\hat{r}_i^kA_i^{fk\prime}\left(\bar{I}_i^{fk}\right)^{-\eta}\right]^\theta}{\sum_{l\in\mathcal{K}^c}\left[r_i^l\hat{r}_i^lA_i^{fl\prime}\left(\bar{I}_i^{fl}\right)^{-\eta}\right]^\theta}\right\}^{1-1/(1-\eta)\theta}, \tag{A45}$$

$$X_i^k\hat{X}_i^k = P_i^kC_i^k\hat{P}_i^k\hat{C}_i^k + \mathbf{1}_{k=0}\left(\sum_{l\in\mathcal{K}^c}P_i^0I_i^l\hat{I}_i^l\right) + \mathbf{1}_{k\in\mathcal{K}^c}\left(P_i^kx_i^k\hat{P}_i^k\hat{x}_i^k\right), \tag{A46}$$

and the aggregate demand for inputs is given by

$$\hat{I}_i^k = \hat{r}_i^k\hat{Q}_i^k. \tag{A47}$$

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 (A40) and (A43), one gets

$$\left[\frac{r_i^k\left(\bar{I}_i^k\right)^{-\eta}}{P_i^0}\right]^{-\theta} = P_i^0\left(R_i^k\right)^{-1}(1-\eta)\,\eta^{\eta/(1-\eta)}\frac{\Gamma\left(1-1/(1-\eta)\,\theta\right)}{\Gamma\left(1-1/\theta\right)}\sum_{f\in\mathcal{F}_i}s_i^f\left(A_i^{fk}\right)^\theta\left\{\sum_{l\in\mathcal{K}^c}\left[\frac{r_i^l\left(\bar{I}_i^l\right)^{-\eta}}{P_i^0}A_i^{fl}\right]^\theta\right\}^{1/(1-\eta)\theta-1}. \tag{A48}$$

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 $r_i^k\left(\bar{I}_i^k\right)^{-\eta}/P_i^0$:

$$\pi_i^{fk} = \frac{\left\{\left[r_i^k\left(\bar{I}_i^k\right)^{-\eta}/P_i^0\right]A_i^{fk}\right\}^\theta}{\sum_{l\in\mathcal{K}^c,r_i^l\geq 0}\left\{\left[r_i^l\left(\bar{I}_i^l\right)^{-\eta}/P_i^0\right]A_i^{fl}\right\}^\theta}, \tag{A49}$$

the values assumed for P_i^0 have no effect on π_i^{fk}. However, in equation (A45), $\hat{Q}_i^k$ 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 thus of Q_i^k, but they have no counterfactual influence.

To calibrate the model with elastic yields, one needs η, which in addition to determining the yield elasticity is also equal from equation (A42) 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 how the initial input costs should be allocated. For crops other than grass, the input costs are taken from the labor share. For grass, it is taken from land.

G 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

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