# Deforestation: A Global and Dynamic Perspective

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**Abstract**

We study deforestation in a dynamic world trade system. We first document that between 1990-2020: (i) global forest area has decreased by 7.1 percent, with large heterogeneity across countries, (ii) deforestation is associated with expansions of agricultural land use, (iii) deforestation is larger in countries with a comparative advantage in agriculture, and (iv) population growth causes deforestation. We build a model in which structural change and comparative advantage determine the extent, location, and timing of deforestation. Using the model, we obtain conditions under which reductions in trade costs and tariffs reduce global deforestation. Quantitatively, eliminating global agricultural tariffs has limited impacts on global forests, leads to substantial forest reallocation across countries, and results in net welfare benefits.

**Keywords**: International trade, deforestation, dynamics, land use

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# 1 Introduction

Global deforestation has gathered speed in recent decades, bringing the adverse impacts of human action on biodiversity and the world's climate to the forefront of public debate. The experiences of individual countries during this period have varied greatly and ranged from substantial deforestation in Brazil to reforestation in China. Seeking to understand these experiences, an important literature has identified several drivers of deforestation, such as international crop prices, infrastructure projects, institutional quality, and trade and environmental policies. World population, moreover, is expected to grow by 25% until 2050, which has renewed concerns about food production and pressures on global land use.

In the face of these concerns, trade policy is emerging as a potential, feasible tool to curb climate change generally and deforestation in particular—to name one example, the EU is working on legislation to ban imports of agricultural products that are linked to deforestation. Agricultural tariff and non-tariff trade barriers, however, have remained high across both developed and developing countries during the past decades and have been a recurrent component in trade negotiations (unlike tariffs in the manufacturing sector). The fact that agricultural trade policy can help mitigate climate change, while there are gains from trade yet to be reaped, calls for an evaluation of the role of global policies to deepen integration in agricultural markets. Such an evaluation is all the most important because previous work, which has thoroughly studied individual countries and industries, is less informative about the evolution of deforestation across countries and over time when government policies and global market conditions change.

We offer an approach that complements previous work by embracing a global and dynamic view of deforestation. The global dimension is crucial because international trade connects the demand for land across countries. For example, an increase in food demand in China can be met with an expansion in Brazil's agricultural frontier, instead of that of China itself. A global perspective makes such spatial linkages explicit and acknowledges that changes to policy or market conditions in one location will have repercussions elsewhere. In turn, a dynamic approach distinguishes between movements in the land frontier, which cause deforestation, and the existing stock of land, which is used in production. This distinction is crucial for understanding the timing of deforestation and associated carbon emissions, one of the main climate damages stemming from it. An approach that is both global and dynamic is therefore important to design policies that have a bearing on deforestation, especially if they are to be applied simultaneously by many countries.

We start by collecting data on land use, sectoral production, international trade, and population growth. Using these data, we document four empirical patterns that describe

the geography of forests and how it relates to international agricultural markets and population growth. First, since 1990 global forest area declined by 7.1 percent—an area the size of Argentina—with substantial heterogeneity across countries. Tropical countries in South America, South East Asia, and Sub-Saharan Africa experienced large rates of deforestation. Put together, these regions account for about 90 percent of the world's forest loss in this period. At the same time, forest area expanded in other regions, such as Europe and China. Second, during this period deforestation across countries was strongly and positively associated with expansions in the agricultural land. This observation suggests that understanding the incentives to use land for agricultural production is crucial to studying deforestation. Third, countries that had a revealed comparative advantage in agriculture in 1990 experienced both a larger increase in agricultural land and in deforestation between 1990 and 2020. This pattern suggests that international trade distributes global pressures on land across countries in line with their comparative advantage in agriculture. Fourth, deforestation in a country follows from growth in its own population and in that of its main trading partners. This fact is important its own right, as worldwide population growth looms large; but it is also informative for our model calibration—the extent to which trade creates a global demand for land informs us about the ease with which the land frontier expands.

Guided by these facts, we develop a dynamic, general-equilibrium model to evaluate the quantitative response of deforestation to trade policy and population growth across the world and over time. The model incorporates many countries that differ in multiple dimensions such as productivity and endowments. It also includes three broad sectors, agriculture, manufacturing, and services that are complementary in consumption and production. There is also a market and, therefore, a price for new land. New land is supplied by a sector that employs labor to transform open-access forests into land. Landowners incorporate new land to their existing stock to rent it to other sectors in the economy. The reallocation of labor between sectors is subject to frictions.

The equilibrium stocks of land and forests in our model are shaped by three mechanisms: (i) structural change determines the size of the agricultural sector and the aggregate demand for land; (ii) comparative advantage distributes pressures on agricultural land use and forests across countries, and together with absolute advantage, determines whether trade alleviates pressures on forests; and (iii) forward-looking land accumulation decisions control the pace of forest adjustments to shocks.

To guide our quantitative analysis, we produce a set of analytical results in a stripped-down version of our model's steady state. First, reducing agricultural export costs unilaterally towards a small open economy leads to deforestation there. The key to this result is that the world import-demand elasticity, i.e., trade elasticity, is positive. Second, and in contrast

to the first result, we show that when countries are symmetric—which shuts down the channel of comparative advantage—a multilateral reduction in iceberg trade costs of agriculture increases global forest area. This is because, when agriculture becomes relatively cheap and agriculture is complementary in consumption with non-agricultural sectors (as in the data), the relative demand for agriculture shrinks. A worldwide reduction in land demand follows, which leads to larger forest area. Third, we examine the impact of a global reduction in agricultural trade tariffs, which differs from a reduction in iceberg trade costs because it does not entail a productivity gain. We obtain here conditions under which a global tariff reduction also increases global forest area. Fourth, we study the role of comparative advantage in a setting with unitary elasticity of substitution between agriculture and non-agriculture, but where productivities differ across countries. We show that the correlation between comparative and absolute advantage in agriculture determines whether trade leads to a gain or loss in global forest area. When this correlation is positive, countries with an absolute advantage in agriculture specialize in agriculture, making the move from autarky to free trade globally land-saving.[1]

We next bring our full, quantitative model to data. We begin by calibrating the parameters that govern the initial equilibrium using production, trade, and forest data from 2010. To do so, we disaggregate the world into 33 countries and 7 regions, and we divide the economy into agriculture, manufacturing, and services, further dividing agriculture into main staple crops, pasture-related products, and a bundle of other agricultural products. We choose the parameters governing the conversion of forest into land so that our model replicates the reduced-form impact of population growth on forest area, at different time horizons.[2]

Second, to ground our quantitative exercises in real-world policy considerations and to ensure our results are not driven by the peculiarities of the iceberg-cost formulation, we examine two additional scenarios involving the elimination of agricultural tariffs. In an analogy with our theoretical results, our first scenario eliminates all agricultural tariffs levied on Brazilian exports, while our second scenario studies a global tariff elimination. Our quantitative results for tariffs are aligned with those for iceberg trade costs—although they are quantitatively smaller. In particular, eliminating tariffs on Brazil leads to a 0.07 percentage point decrease in global forest cover, while eliminating them globally leads to a 0.17

[1]Taken together, these results extend the famed Borlaug's hypothesis—that agricultural productivity growth is land-saving in a closed economy Borlaug (2000)—to the domain of international trade, explaining the consequences to changes in different types of trade barriers and highlighting that trade can lead to global forest gains.

[2]Our quantitative model features, in addition, a fallow land sector. We introduce this block to capture the fact that in the data fallow land is a sizable share of total land and an important source of expansion in agricultural land.

percentage point increase.

We then show the quantitative importance of the adjustment mechanisms using our second policy scenario, complementing our analytical results. First, agricultural tariff liberalization leads to deforestation at the global level when the elasticity of substitution between broad sectors is large (i.e., when price effects make structural change operate against forests). Second, comparative advantage in agriculture plays a dual role: it determines the cross-section of deforestation and, in line with the observed positive correlation between absolute and comparative advantage in agriculture, moving toward free trade seems to alleviate the global pressure on forests.

Having established the quantitative importance of the key mechanisms in our model, we create a new Business-as-usual (BAU) scenario in which each country's population grows according to the UN projection in coming decades. In this new BAU scenario, many African countries experience large rates of deforestation since their growing population increases local demand for food. We find that the scope for tariff reductions to mitigate the effects of population growth on deforestation is limited in this context.

We conclude by evaluating the $CO_2$ emissions costs brought about by deforestation,[3] and and associated welfare changes in policies we examine. We do so under a broad range of assumptions, so as to highlight the role of different economic mechanisms and measurement approaches that allow for reforestation, carbon heterogeneity or carbon sequestration. In our simplest exercise, the climate costs of export costs reductions in the global versus Brazil-only scenario are roughly the same, despite the large difference in their global welfare impact. In turn, including the sequestration benefits of new forests in our calculation or considering a BAU that includes population growth turns the climate costs of global trade cost reductions into gains.

We contribute to research at the intersection of trade, spatial economics, and the environment. Costinot et al. (2016) and Gouel and Laborde (2018) study the extent to which trade mitigates the impacts of climate change. Other recent studies have formulated dynamic trade and migration models to evaluate the consequences of climate change (e.g. Desmet et al., 2018; Conte et al., 2020; Balboni, 2019). Kortum and Weisbach (2022) and Farrokhi and Lashkaripour (2024) study instead the design of optimal trade and carbon policy on global carbon emissions. Shapiro (2016) evaluates the impact of international shipping on $CO_2$ emissions. A few recent papers study quantitatively the relations between trade and natural resources. For example, Farrokhi (2020) studies the impact of trade-related policies in global

[3]This evaluation adheres to the guidelines routinely used by the International Panel on Climate Change. While we acknowledge the negative impacts of deforestation on biodiversity and amenities, we do not intend to examine them.

oil markets, and Carleton et al. (2023) examine the relation between agricultural trade and the allocation of water use across the world. Focusing on deforestation, Dominguez-Iino (2021) examines the effects of environmental policies along supply chains in South America, and Hsiao (2021) studies international cooperation and commitment in the market for palm oil, also in a dynamic context. See Copeland and Taylor (2004) and Copeland et al. (2021) for a review of previous work. Closer to our research is Hertel (2012), who points out that the impact of agricultural technological innovations on land use and emissions depends on the elasticity of demand faced by farmers. Relative to this literature, we are the first to incorporate deforestation dynamics into a quantitative general equilibrium framework to study how economic forces and international trade policy shape land use around the world. Our multi-country equilibrium approach demonstrates the role of structural change and comparative advantage in shaping the deforestation impact of trade openness.

Second, we contribute to research examining the welfare impacts of agricultural trade (Donaldson, 2018; Sotelo, 2020; Pellegrina, 2020) and how agriculture relates to structural change and development (Tombe, 2015; Fajgelbaum and Redding, 2014; Farrokhi and Pellegrina, 2020; Gollin et al., 2018). Our work gives deforestation a central role in the analysis of agricultural trade, focusing on how structural change determines worldwide pressures on land use and how the resulting impact on deforestation evolves over time. We also relate to a long-standing and rich tradition, reviewed in Hertel (2002), that formulates computational general equilibrium (CGE) models to study global agricultural markets. Relative to the latter, we introduce dynamics in land development and we provide an analytical characterization of the mechanisms driving global deforestation.

Lastly, we complement a large literature that uses detailed micro-data to study different drivers and consequences of deforestation and forest management, including the role of national institutions (Burgess et al., 2019), land use taxes and payment programs for forest conservation (Jayachandran et al., 2017; Assunção et al., 2020; Souza-Rodrigues, 2019; Araujo et al., 2022), roads and access to markets (Pfaff, 1999; Araujo et al., 2023; Gollin and Wolfersberger, 2024; Asher et al., 2020) and regional trade agreements (Abman and Lundberg, 2020; Abman et al., 2024), China's demand for food Hansen and Wingender (2023), demand for wood and forest products (Foster and Rosenzweig, 2003), spatial misallocation in agricultural deforestation (Mishra, 2025), and externalities generated by forest fires (Balboni et al., 2020). We examine how incentives to deforest transmit across countries through international trade, emphasizing that government policies and market conditions in one country have the potential to drive or curb deforestation elsewhere.

# 2 Data sources

We combine data on global deforestation and carbon content of forests with other, more standard country-level information on trade, production, and factor employment required in global trade models. After merging these data sets, we have 150 countries in five periods (1990, 2000, 2010, 2015 and 2020). Later, we group countries into 40 countries and regional aggregates to quantify our model. Below we summarize our data. Appendix A provides additional details about each data source.

**Forests and Forest Carbon Stock** Since 1948, FAO has published a periodic report called Forest Resource Assessment (FAO-FRA), which reflects the FAO's efforts to measure country-level forest area from national forest inventories. We focus on this data set for two reasons. First they are publicly available and they offer ample coverage in time and space. The data that we use come from the latest edition of FRA, FAO (2020), which covers a 30-year period between 1990 and 2020. Second, it is a key reference for policy debate on global deforestation and for assessments of the impact of deforestation on climate change (Brown and Zarin, 2013).[4]

We also employ FAO-FRA information on the carbon content of living biomass above ground—which includes all living biomass above the soil—as well as below ground—which incorporates all biomass of living roots.

**Other Country-level Data.** We use data on agricultural production, land use, and international trade, disaggregated by agricultural commodity, from FAO-STAT. For agriculture, manufacturing and services, we take data on employment from UN-ILO and value added, final and intermediate-input expenditures, and international trade from the GTAP database.

# 3 Four Empirical Patterns about Global Deforestation

This section documents four empirical patterns about global deforestation that motivate our modeling approach. We first document the evolution of deforestation between 1990 and 2020. Second, we show that deforestation has been strongly associated with expansions in agricultural land use. Third, deforestation was larger in countries with a comparative

[4]These data are used, for example, for the estimation of $CO_2$ emissions from deforestation by the Intergovernmental Panel on Climate Change (IPCC). Since the 1990s, the methodology used by FAO has been improved to ensure that the measurement of forest areas are comparable over years. This is the earliest year for which we can build consistent time series.

advantage in agriculture. Fourth, population growth within a country and also among its main trade partners drives deforestation in that country.

**Pattern 1. Between 1990 and 2020, global forest area dropped by 7.1%. While in the tropics, forest area dropped substantially, in several non-tropical regions there was forest regrowth.**

In what follows, we use "country area" as a shorthand for total area of a country net of deserts, glaciers and lakes. Panel (a) in Figure 1 shows the share of country area covered by forest. Countries with higher forest concentration tend to be close to the North Pole, including Canada, Russia, and the Nordic countries that host large boreal forests, or near the equator, where the tropical forests of the Amazon, Congo Basin, and Southeast Asia are located. Panel (b) depicts global deforestation in 2020 relative to 1990 (as percentage points of the each country's area). The 7.1% loss of global forest area—from 4.07 to 3.78 billion hectares—amounts to the size of a country larger than Argentina. Deforestation was particularly substantial in tropical countries such as in Brazil, Congo, and Indonesia where their forest area fell respectively by 17%, 16%, and 26% during this period.[5] Other countries, primarily China and many European countries, reforested over this period.

The correlation between a country's forest share in 1990 and its deforestation between 1990-2020 is sizable, equal to 0.57, and statistically significant. In our quantitative model, we introduce a land-clearing technology whose productivity depends on the current share of forest, so as to respect this feature of the data.

Appendix Table H.2 provides an accounting of global deforestation disaggregated by the 33 countries plus 7 aggregate regions we bring to data for quantitative analysis.[6] The table shows for each country the forest share in country area in 1990, percentage point change in forest share and percentage change in forest area during 1990-2020. It also shows each country's contribution to the global deforestation during 1990-2020. Brazil alone accounts for one-third of global deforestation, followed by Central African countries and Indonesia together accounting for one-fourth of global deforestation. Our model aims at capturing economic mechanisms driving these different deforestation.

Before moving on, we note that forests are heterogeneous in their carbon content. Figure H.1 in the appendix depicts each country's forest carbon intensity (tons of carbon stock per

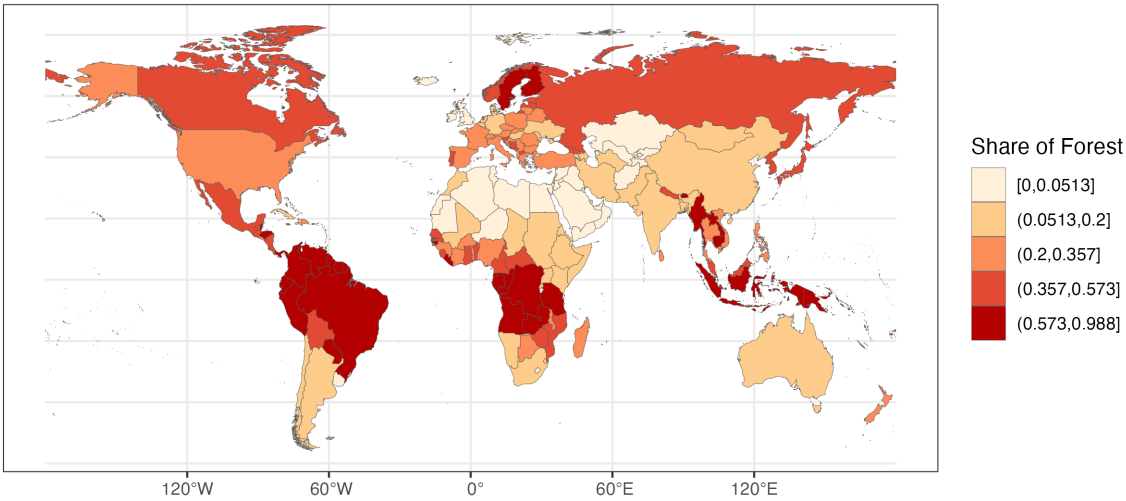
[5]The figure shows these numbers in terms of the percentage point (p.p.) change in each country's forest share rather than percentage change since the latter gives uninformatively large magnitudes in countries where forest share is tiny. The p.p. change in forest share (multiplied by 100) was -2.2 at the global level and -12.0, -10.8, and -16.4 respectively in Brazil, Congo, and Indonesia.

[6]Appendix Table H.4 reports these deforestation-related variables at the individual country level and Appendix Table H.1 lists the individual countries that constitute each of our regional aggregates.

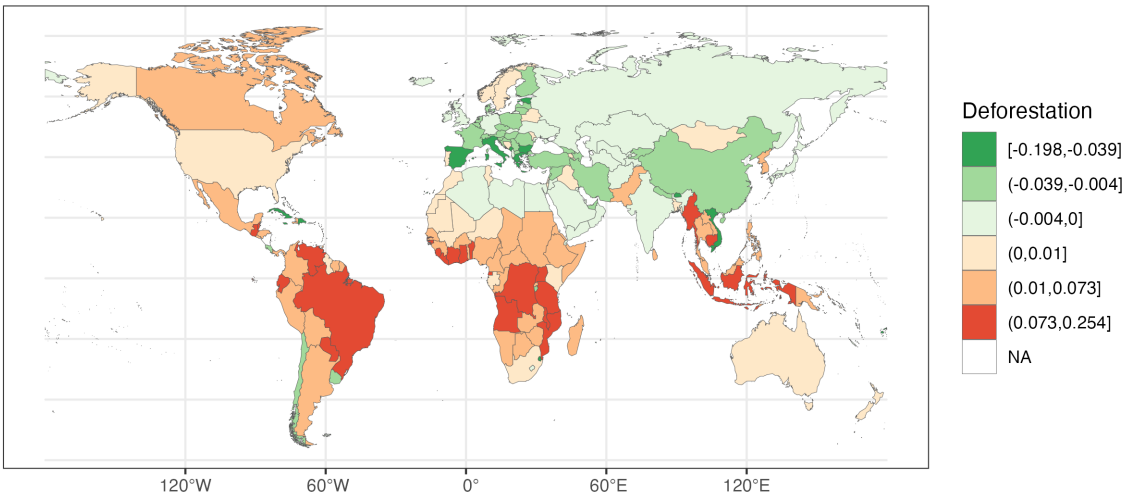
hectare of forest), suggesting that the carbon emission implications of deforestation depend on where it occurs. We incorporate this heterogeneity into our analysis of the climate costs of different trade integration scenarios, following the IPCC and FAO guidelines (Tubiello et al., 2020).

Figure 1: Forest and Deforestation across the World (1990-2020)

(a) Forest share in Country Area (1990)




(b) Deforestation (2020 relative to 1990)



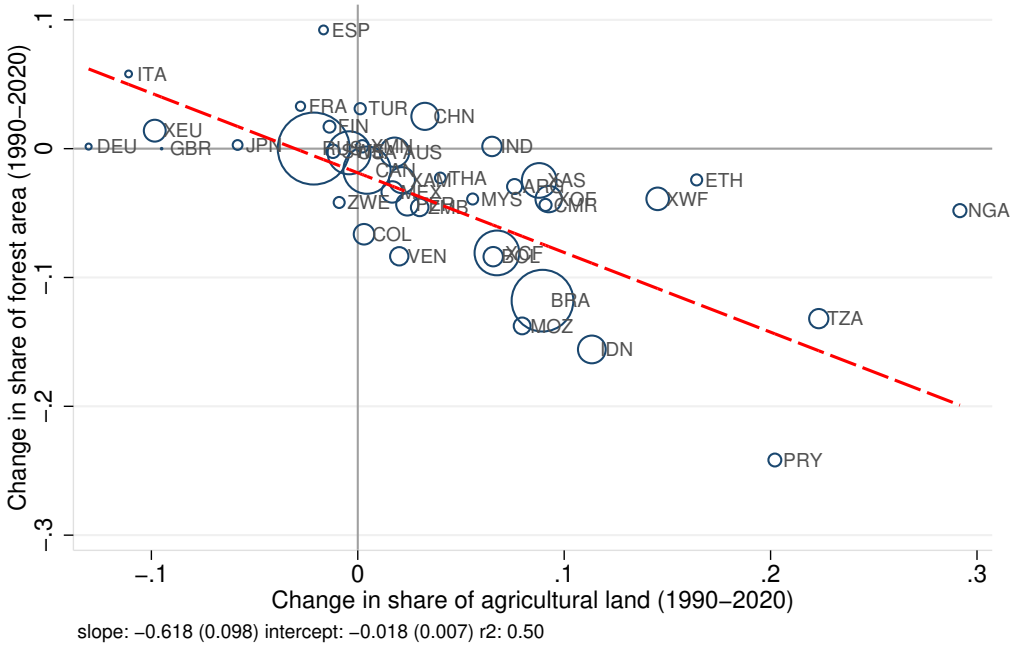

**Notes**: Panel (a) shows "forest share" for each country—as the share of a country's area covered by forest in 1990. Panel (b) shows the percentage point change in forest share for each country between 1990 and 2020.

**Pattern 2. Changes in forest area are negatively correlated with changes in agricultural land use.**

Figure 2 plots the change in forest area against the change in agricultural land use across countries, both measured as a share of their corresponding country area. The two variables are strongly and negatively correlated, with the share of forest area decreasing at a slope of -0.62 with respect to the share of agricultural land. Note that the relationship does not lie exactly along the negative 45 degree line. This deviation may be partly explained by agricultural land expanding onto non-forest land, such as fallow land areas.[7]

This empirical regularity motivates us to design a land-use model in which expansions in land use, particularly from agriculture, may come at the cost of deforestation. We next turn to two mechanisms driving the demand for agricultural land in a country, namely, agricultural trade and population growth.

Figure 2: Change in Share of Land in Forest versus Share of Land in Agriculture (1990-2020)




***Notes***: This figure shows the relationship between changes from 1990 to 2020 in agricultural land use and changes forest area across countries, each as a share of country area, in percentage changes from 1990 to 2020. The size of circles represents the total forest area in each country. The red dashed line shows the linear fit weighting the observations by each country's forest area in 1990.

[7]See Appendix Figure H.2 for each region in our data, the share of land under forest, agriculture, and a residual "fallow land" category that we construct as the difference between country area and the sum of forests and agricultural land (excluding water bodies and other non-productive areas, such as deserts). Fallow land takes as much as fifty percent of the land in countries like Argentina but less than 20 percent in Brazil. Later in the paper, we incorporate data on fallow land in the calibration of our quantitative model.

**Pattern 3. Between 1990 and 2020, countries with a comparative advantage in agriculture experienced a larger expansion in their agricultural land use and a larger reduction in their forest area.**

We next examine countries' change in agricultural and forest area in relation to their comparative advantage in agriculture. To this end, we employ the index of revealed comparative advantage for each country $i$, defined as:

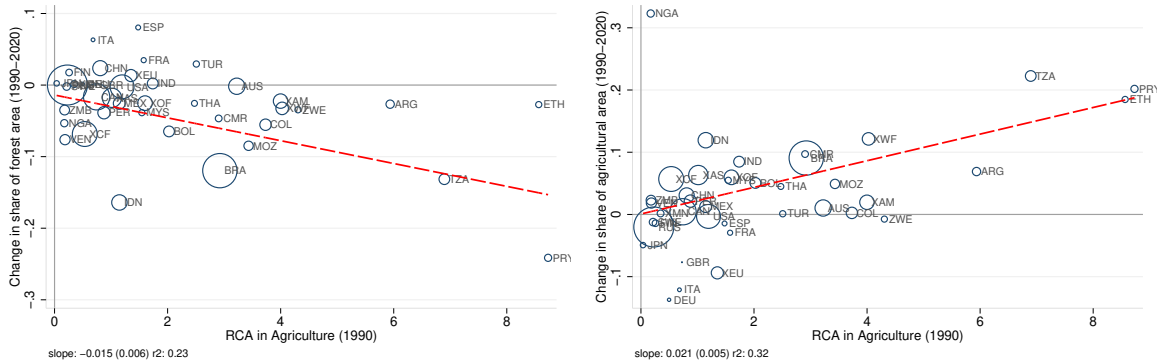
$$\text{RCA}_i^{(\text{Agr})} = \frac{(\text{Agr Exports})_i/(\text{Total Exports})_i}{(\text{World Agr Exports})/(\text{World Total Exports})},$$

i.e., the degree to which a country $i$'s exports specialize in agriculture, relative to those of the rest of the world. Panels (a) and (b) of Figure 3 show that in countries with a higher RCA (measured in 1990) the expansion agricultural land and the reduction of forest area was larger between 1990 and 2020. This pattern motivates a model in which comparative advantage governs the relative demand for land, and therefore the pressure on forests, across countries.

Figure 3: Change in Agricultural Land and Forest Area against Comparative Advantage in Agriculture

(a) Forest area

(b) Agricultural area

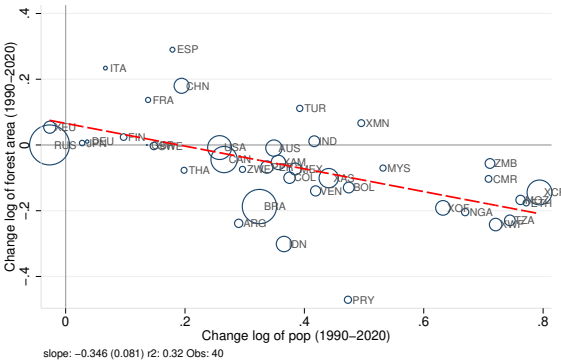



**Notes**: This figure shows the 1990-2020 change in agricultural land share in country area (Panel a) and forest share in country area (Panel b) against the index of revealed comparative advantage (measured in 1990) across countries.

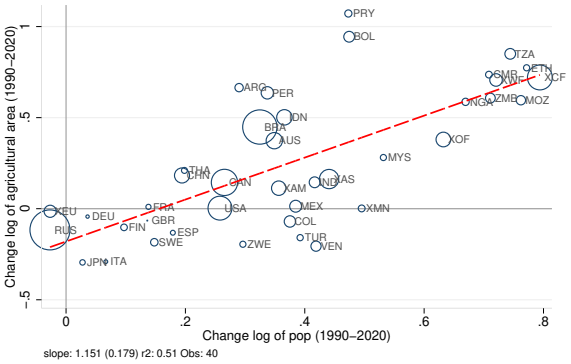
**Pattern 4. Domestic population growth and that of top trading partners leads to agricultural land expansion and deforestation.** Figure 4, Panels (a) and (b) show that population growth in a country is associated with contractions in forest area and increases in agricultural land. In addition, Figure 5, Panels (a) and (b) show that when population grows in a country's top five trade partners, that country's forest area shrinks and its agricultural area expands, as well.

Figure 4: Change in Forest and Agricultural Area on Domestic Population Growth

(a) Forest Area



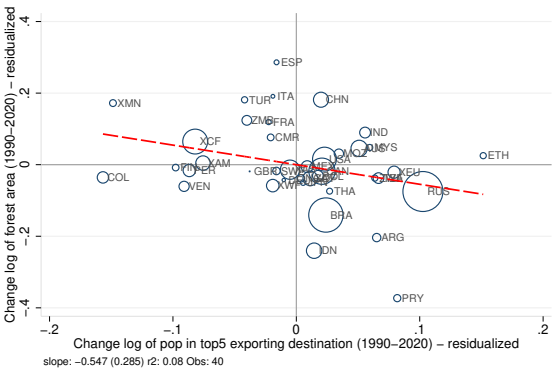

(b) Agricultural Area



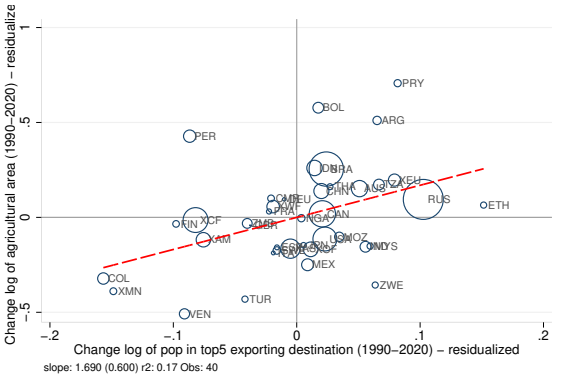

**Notes**: This figure shows the 1990-2020 change in log agricultural land area (Panel a) and log forest area (Panel b) against the 1990-2020 change in log population across countries.

Figure 5: Change in Forest and Agricultural Area on Top trade Partner's Population Growth

(a) Forest Area




(b) Agricultural Area




**Notes**: This figure shows the 1990-2020 change in log agricultural land area (Panel a) and log forest area (Panel b) against the 1990-2020 change in log population across countries. We residualize the y- and x-axis variables based on the population growth of a country's own population.

To explore this relationship more systematically, we consider the following equation:

$$\Delta \ln y_{i,t} = \beta_0 + \beta_1 s_{i,t}^{\text{Own}} \Delta \ln \text{Own Population}_{i,t} + \beta_2 s_{i,t}^{\text{Partner}} \Delta \ln \text{Partner Population}_{i,t} + \beta_X \mathbf{X}_{i,t} + \epsilon_{i,t} \tag{1}$$

where $y_{i,t}$ represents either agricultural land or forest area; Own Population$_{i,t}$ and Partner Population$_{i,t}$ measure country $i$'s population and that of its top 5 trading partners, and $\mathbf{X}_{i,t}$, and $\epsilon_{i,t}$ control variables—see description in the table—and the error term for country $i$ at time $t$. The $\Delta$ operator denotes 30-year time differences. The coefficients of interest are $\beta_1$ and $\beta_2$, which capture the impact of domestic population growth and that of country $i$'s top 5 trading

partners on net forest or agricultural land growth. We adjust these variables by the share of agricultural sales of a country to itself $s_i^{\text{Own}}$ and share of sales to top trading partners $s_i^{\text{Partern}}$ in year $t-1$.

An OLS estimation of equation (1) may suffer from endogeneity bias. For example, shocks to agricultural productivity can lead to a change to both population and deforestation, creating a correlation between population growth and the error term. We therefore instrument $\Delta \ln \text{Own Population}_{i,t}$ with the median age of the population, the crude birth rate per 1000 individuals, and the average age for child bearing at time period $t-1$. Likewise, we instrument $\Delta \ln \text{Partner Population}_{i,t}$ with these same three variables in country $i$'s top trading partners.[8] Our identifying assumption is that, conditional on our set of controls (which include GDP per capita and measures of forest area protection) past demographic structure is uncorrelated with current productivity shocks, so the instruments predict population growth for purely biological reasons.

Table 1 shows the OLS and IV estimates of equation (1). Overall, Panel (a) reports negative elasticities of forest area to both population variables, for both OLS and IV, without any controls (Columns (1) and (4)), with controls for initial forest and agricultural area (Columns (2) and (5) and with additional controls for natural areas under reservation and GDP per capita (Columns (3) and (6)). Our formulation adjusts the population growth shock by a revenue share, so that the regressors of interest can be interpreted as local and foreign shocks to agricultural demand. It also implies that the elasticity of our dependent variables to population growth is heterogenous across countries. For the average country in the sample, the share of domestic sales in total sales is 0.85, while the share of sales to its top trading partners is 0.12. Thus, the IV estimate under Column (6) implies that a 10 percent increase in own population growth reduces its forest area by $3.6 \times 0.85 = 3.06$ percent, while a 10 percent increase in the country's trading partners' population reduces its forest area by $11.9 \times 0.12 = 1.43$. A comparison show that the elasticity of forests to local demand is about twice as large as that in response to foreign demand.

Panel (b) retains the same structure, only placing agricultural area as a dependent variable. Across specifications, the coefficient is positive and statistically significant. For the average country in our sample, the IV estimate in Column (6) indicates that a 10 percent increase in population leads to a $8.8 \times 0.85 = 7.48$ percent increase in agricultural land use, while a 10 percent increase in population of the country's top trading partners leads to a $29.9 \times 0.12 = 3.59$ percent increase in agricultural land use. Once again, we can see that the

[8] To construct the population growth in partner countries, we aggregate the total population across the 5 top trading partners of a country in every year, effectively making it a larger geographic unit. To construct the instruments and controls, we take the average of the these values at $t-1$ across trading partners.

impact of local demand on local land is about twice as large as the effect of foreign demand. Appendix Table H.6 shows that our qualitative results are largely the same if we use the full sample of countries.

These results are important in their own right, for at least three reasons. First, because the world population is expected to grow by 35 percent between 2020 and 2100, our results are informative about the impact of a shock that looms large in the future. Second, our results cement the notion that international trade distributes pressures on land demand across countries. Third, through the lens of our model, changes in population map transparently into land use pressures, both by raising the demand for food and increasing the supply of labor. We will therefore target these reduced-form results to calibrate the parameters of our land-producing sector, which governs the response of deforestation to shocks to fundamentals (including trade costs).

Table 1: The Relationship between Population Growth and Forest Area (30 years interval)

| | OLS | OLS | OLS | IV | IV | IV |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| *a. DV is the log of forest area* | | | | | | |
| $s^{\text{Own}} \times \Delta$ Log(Own Pop) | -0.380*** | -0.357*** | -0.257* | -0.436*** | -0.408*** | -0.360* |
| | (0.072) | (0.065) | (0.151) | (0.095) | (0.084) | (0.197) |
| $s^{\text{Partner}} \times \Delta$ Log(Partner Pop) | -1.325* | -1.209 | -1.030 | -1.416** | -1.295* | -1.190* |
| | (0.727) | (0.742) | (0.766) | (0.708) | (0.711) | (0.721) |
| R2 or K-P | 0.310 | 0.360 | 0.403 | 34.995 | 32.726 | 12.313 |
| Obs | 40 | 40 | 40 | 40 | 40 | 40 |
| *b. DV is the log of agricultural area* | | | | | | |
| $s^{\text{Own}} \times \Delta$ Log(Own Pop) | 1.409*** | 1.368*** | 1.136*** | 1.427*** | 1.375*** | 0.879*** |
| | (0.106) | (0.111) | (0.225) | (0.107) | (0.102) | (0.297) |
| $s^{\text{Partner}} \times \Delta$ Log(Partner Pop) | 3.809*** | 3.629*** | 3.177*** | 3.864*** | 3.632*** | 2.986*** |
| | (0.872) | (0.952) | (0.888) | (0.840) | (0.913) | (0.904) |
| R2 or K-P | 0.746 | 0.761 | 0.815 | 34.995 | 32.726 | 12.313 |
| Obs | 40 | 40 | 40 | 40 | 40 | 40 |
| Controls (Initial period value in logs) | | | | | | |
| - Share of Agricultural area | - | Y | Y | - | Y | Y |
| - Share of Forest area | - | Y | Y | - | Y | Y |
| - Natural reserve area | - | - | Y | - | - | Y |
| - GDP p.c. | - | - | Y | - | - | Y |

**Notes**: * / ** / *** denotes significance at the 10 / 5 / 1 percent level. Robust standard errors clustered at the country level in parenthesis. Instrument in columns (4) to (6) are (1) the log of the median age of the population, (2) the birth rate, and (3) the average age of child bearing in the baseline year. Kleinberg-Paap weak instrument statistic is reported in columns (4) to (6) instead of R2.

**Remarks on the empirical patterns.** The empirical patterns discussed above motivate a dynamic, quantitative model of global trade and land use. Fact 1 suggests that the pace of deforestation depends, among other forces, on a country's current forest stock. Fact 2 shows that expansions in agricultural activity account for a substantial share of deforestation

across countries. Fact 3 indicates that countries exploit their comparative advantage in agriculture, in part, by deforesting. Fact 4, in turn, confirms the role of international trade by showing that population growth in trade partners, together with own population growth, cause deforestation. Before describing the model we use for quantification, in the next section we outline a stripped down version, which we use to derive analytical results that guide the interpretation of our quantification.

# 4 The Stylized Model

Consider a global economy consisting of multiple countries, indexed by $i, j = 1, ..., N$, and three sectors: agriculture ($A$), manufacturing ($M$), and land-clearing ($T$). Time is continuous and denoted by $t \in [0, \infty)$. Each country $i$ is endowed with (i) a fixed amount of land $H_i$, which consists of agricultural land, $L_i(t)$, and forest area, $F_i(t)$, such that $H_i = L_i(t) + F_i(t)$, and (ii) a labor force $N_i(t)$, which evolves exogenously over time. Labor is perfectly mobile within each country and immobile between countries. Markets are perfectly competitive. Hereafter we drop the time index with the understanding that all variables may vary over time, and we denote the time derivative of any variable $x$ by $\dot{x}$.

**Households.** Each country has a representative consumer with a two-tier constant elasticity of substitution (CES) demand. In the lower tier, national varieties of $g = \{A, M\}$ are aggregated with an elasticity of substitution $\eta$ into a composite bundle of $g$. In the upper tier, the composite bundles of $A$ and $M$ are combined into an aggregate consumption bundle, with an elasticity of substitution $\sigma$.

The lower tier gives rise to international trade flows in agriculture and manufacturing. Specifically, country $j$'s share of expenditure on origin $i$'s variety of $g = \{A, M\}$ equals:

$$\pi_{ij,g} = \left( \frac{p_{ij,g}}{P_{j,g}} \right)^{1-\eta}, \tag{2}$$

where $P_{j,g}$ is the consumer price of $g$ in country $j$:

$$P_{j,g} = \left( \sum_{n=1}^{N} p_{nj,g}^{1-\eta} \right)^{1/(1-\eta)} \tag{3}$$

The upper tier, in turn, determines the expenditure across broad sectors in the economy.

Specifically, country $j$'s expenditure share on sector $g = \{A, M\}$ is given by:

$$\beta_{j,g} = \left( \frac{P_{j,g}}{P_j} \right)^{1-\sigma}, \tag{4}$$

where $P_j$ is the final consumer price index:

$$P_j = \left( P_{j,A}^{1-\sigma} + P_{j,M}^{1-\sigma} \right)^{\frac{1}{1-\sigma}}. \tag{5}$$

**Production.** Technologies are given by:

$$Q_{i,A} = Z_{i,A} L_i, \qquad Q_{i,M} = Z_{i,M} N_{i,M}, \qquad Q_{i,T} = Z_{i,T} N_{i,T}, \tag{6}$$

where agriculture uses only land, while manufacturing and land-clearing use only labor. $Z_{i,A}$, $Z_{i,M}$ and $Z_{i,T}$ are exogenous productivity parameters. In each country, the land-clearing sector converts the forest area into the agricultural land.[9] The products of agriculture and manufacturing are differentiated by origin country and traded internationally between each origin $i$ and destination $j$ subject to trade costs $\tau_{ij,g} = (1 + t_{ij,g})\, d_{ij,g}$ for each $g = \{A, M\}$, where $t_{ij,g}$ denotes ad valorem import tariff rates charged by country $j$ to country $i$, and $d_{ij,g} \geq 1$ represents iceberg trade costs for shipping goods from $i$ to $j$ (with $t_{ii,g} = 0$ and $d_{ii,g} = 1$). Consequently, the price of $g = \{A, M\}$ from origin $i$ at destination $j$ equals:

$$p_{ij,A} = \frac{\tau_{ij,A} r_i}{Z_{i,A}}, \qquad p_{ij,M} = \frac{\tau_{ij,M} w_i}{Z_{i,M}}; \tag{7}$$

where $r_i$ is the rental rate of land, and $w_i$ is the wage rate in country $i$. In turn, the price of new land, denoted by $q_i$, is set domestically in the land-clearing sector,[10]

$$q_i = \frac{w_i}{Z_{i,T}}. \tag{8}$$

**Landowners.** A continuum of symmetric landowners, who are risk-neutral and have perfect foresight, connect the land-clearing sector to the agricultural sector. Each landowner owns one unit of land that can be rented out at the rate $r_i$ to agricultural producers. Landowners discount the future at a rate of $\rho$, and each unit of land "depreciates" back into forest at an arrival rate of $\delta_L$. Under these assumptions, the value function $v_i^L$ of a landowner can be

[9] In the corner case of $F_i = 0$, the production flow of the new land becomes zero, $Q_{i,T} = 0$.

[10] We write the pricing conditions 7 and 8 under the assumption that both $M$ and $T$ are operational, which will always be true with Armington differentiation.

expressed as:

$$\rho v_i^L = r_i - \delta_L v_i^L + \dot{v}_i^L.$$

Potential entrants may purchase new land produced by the $T$ sector when $v_i^L$ is greater than or equal to the price of new land, $q_i$, with the free entry condition ensuring that $v_i^L = q_i$. Hence, the price of new land satisfies the following asset pricing equation:

$$(\rho + \delta_L)\, q_i = r_i + \dot{q}_i. \tag{9}$$

Solving this equation delivers the price of new land as the present value of future land rents, discounted by $(\rho + \delta_L)$, a rate that accounts for both time preference and forest regrowth.[11]

Finally, agricultural land grows with the inflow of new land converted from forest by the $T$ sector, $Q_{i,T}$, and shrinks with the outflow due to forest regrowth, $\delta_L L_i$,

$$\dot{L}_i = Q_{i,T} - \delta_L L_i. \tag{10}$$

The economy evolves from an initial state toward the steady state.[12] The transitional path between these two states ensures a sequence of static equilibria through market clearing at each point in time, connected over time through dynamics of land use. Below, we formally define these relationships.

**Market clearing.** National expenditure in country $i$, $E_i$, equals net payments to labor and land plus tariff revenues, $T_i$:

$$E_i = w_i N_i + (r_i L_i - w_{i,T} N_{i,T}) + T_i,$$

where

$$T_i = \sum_{g \in \{A,M\}} \sum_n \frac{t_{ni,g}}{1 + t_{ni,g}} X_{ni,g}.$$

Total payments to land come from sales across the world:

$$r_i L_i = \sum_j \frac{X_{ij,A}}{1 + t_{ij,A}}, \tag{11}$$

[11] Specifically, $q_i(t) = \int_t^\infty e^{-(\rho+\delta_L)(s-t)} r_i(s)\, \mathrm{d}s$.

[12] We suppose that all exogenous variables, such as each country's population, technology, etc., reach a constant value as $t \to \infty$.

and, likewise, for manufacturing labor:

$$w_i N_{i,M} = \sum_j \frac{X_{ij,M}}{1 + t_{ij,M}}. \tag{12}$$

**Static Equilibrium.** Given (i) technologies, iceberg trade costs, tariffs, and preferences $\{Z_{i,g}, d_{ij,g}, t_{ij,g}, \sigma, \eta\}$, (ii) agricultural land and national labor supplies $\{L_i, N_i\}$ ,and (iii) the price of new land $\{q_i\}$, a static equilibrium consists of factor rewards $\{w_i, r_i\}$ and labor allocations $\{N_{i,T}, N_{i,M}\}$, such that land markets clear according to (11) and labor markets clear according to (8) and (12).

**Dynamic Equilibrium.** Given (i) paths of technologies, iceberg trade costs, tariffs, preferences and national labor supplies, and (ii) initial agricultural land $\{L_i(0)\}$, a dynamic equilibrium consists of the paths of static equilibrium variables as well as price of new land and stock of agricultural land $[\{q_i(t), L_i(t)\}]$ that evolve according to Equations 9 and 10.

**A Steady-State Equilibrium.** A steady-state equilibrium is a dynamic equilibrium in which $\dot{q}_i = \dot{L}_i = 0$.

In Section 6, we extend this stylized model in several ways to bring it to data for quantitative analysis.[13] Before doing so, however, we use it to derive a few key analytical results under steady-state equilibrium.

To set the stage for our analysis in the next section, we conclude this section by showing how the variables in the land-clearing sector are linked to those in the agricultural sector. In the steady state, Equations 8 and 9 imply that the rental rate of land is proportional to the wage rate through the following relationship:

$$r_i = \frac{(\rho + \delta_L) w_i}{Z_{i,T}}.$$

Furthermore, replacing $Q_{i,T}$ from Equation 6 into the steady state version of Equation 10 establishes a link between agricultural land area and employment in the land-clearing sector,

$$L_i = \frac{1}{\delta_L} Z_{i,T} N_{i,T}.$$

[13]These extensions include: (i) incorporating a service sector and disaggregating the agricultural sector, (ii) introducing an input-output structure to production technologies, (iii) forward-looking labor decisions with sectoral switching costs, (iv) adding a third category of land, which we refer to as "fallow," and (v) allowing the productivity in the land-clearing sector to depend on the available stock of forest and fallow land. Crucially, we also solve for the entire transitional path when evaluating policy responses.

The two equations above show how the steady state values of the rental rate and area of agricultural land depend on labor market outcomes. These relationships arise because the agricultural land is ultimately produced using labor. In this sense, the steady state reflects the long-run outcome of the balance between human-driven, economic incentives to expand agricultural land and the natural tendency of forests to regrow. Do changes in international trade costs shift this balance by mitigating the pressures to deforest, or do they amplify them instead? Our analysis in the next section examines this question.

# 5 Analytical Results

This section uses our stylized model to provide four analytical results that characterize the impact of trade on deforestation and that guide the interpretation of our quantitative results below. First, when a small open economy experiences reductions in its export costs, it loses forests. Second, and in contrast to our first result, in a world consisting of symmetric countries, a multilateral reduction in iceberg agricultural trade costs results in global forest gain. Third, provided that the initial level of tariffs is sufficiently high, a global reduction in tariffs also results in global forest gain. Fourth, in a world consisting of asymmetric economies, trade leads to a global forest gain if comparative and absolute advantage in agriculture align across countries. Appendix B collects the proofs.

Our first proposition clarifies the context in which a conventional intuition—that trade leads to deforestation—can be most clearly understood. To this end, we consider country $i$ as a small open economy á la Alvarez and Lucas (2007) and drop the country indicator $i$.

**Proposition 1.** *A unilateral reduction in the export costs faced by a small open economy leads to an increase in its stock of land, governed by:*

$$\frac{\mathrm{d}\ln L}{\mathrm{d}\ln d_A} = \frac{N_M}{N}(1-\eta) < 0 \quad \textit{for} \quad \eta > 1. \tag{13}$$

The response in the stock of land is governed by the elasticity of substitution between domestic and foreign varieties, $\eta$. Specifically, the elasticity of derived demand for land coincides with the elasticity of import demand, $(1-\eta)$. In the empirically-relevant case, this elasticity is negative. Consequently, a reduction in export costs in a small open economy leads to deforestation.

In contrast, multilateral trade cost reductions can have a markedly different impact on deforestation. Suppose that all countries in the world are symmetric, in the sense that they have the same endowments, geography and productivity, and suppose as well that there are no tariffs. Under symmetry, we can drop the country indicator $i$. The next proposition shows

that, in contrast to Proposition 1, a global reduction in trade costs leads to an expansion in global forest area.

**Proposition 2.** *A global reduction in agricultural trade costs in a system of symmetric economies leads to a decrease in the global stock of land, governed by:*

$$\frac{\mathrm{d}\log L}{\mathrm{d}\log d_A} = \frac{N_M}{N}(1-\sigma)\left(1-\pi_A^D\right) > 0 \quad \textit{for} \quad \sigma < 1; \tag{14}$$

*where $\pi_A^D$ is the domestic expenditure share in the agriculture sector.*

Here, the response of the land stock is governed by the elasticity of substitution between agriculture and manufacturing sectors, $\sigma$. In the empirically relevant case, agriculture and manufacturing are complements, i.e. $\sigma \in (0,1)$, and so, a trade cost reduction results in a reduction in agricultural land and hence an expansion of forest area. The reason is that, in response to the change in prices, structural change reallocates resources away from agriculture and deforestation. In other words, at the global level, because demand for land is sufficiently inelastic, the productivity gains from trade cost reductions lead to land savings.

The above result is stark and highlights the workings of one of the key mechanisms in the model. It relies, however, on the assumption of iceberg trade costs, where payments for agricultural trade costs are fully received by farmers, and as a result, entirely allocated to land. Because a reduction in iceberg-type agricultural trade costs is an export-biased productivity gain, it can reduce land use beyond its impact on the land content of agricultural consumption. The next result provides conditions under which a global tariff reduction leads to forest growth.

**Proposition 3.** *Consider a worldwide change in agricultural (ad valorem) import tariffs in a system of symmetric economies. As a result:*

*(i) The global stock of land changes according to:*

$$\frac{\mathrm{d}\ln L}{\mathrm{d}\ln(1+t_A)} = \frac{N_M}{N}\left[\underbrace{(1-\sigma)\left(1-\pi_A^D\right)}_{(+)\ if\ \sigma<1} + \underbrace{\frac{h_A}{1-h_A}(\eta-1)\,\pi_A^D}_{(+)\ if\ \eta>1} + \underbrace{\frac{-1}{1-h_A}\frac{1-\pi_A^D}{1+t_A}}_{(-)}\right], \tag{15}$$

*where $h_A = \frac{t_A}{1+t_A}\left(1-\pi_A^D\right)$ is the fraction collected as tariffs from a dollar spent on agriculture.*

*(ii) In response to a worldwide reduction in agricultural tariffs: Provided that $\eta > \sigma$, the global stock of land increases when tariffs are sufficiently low, $t_A \in [0, t_A^*)$, and decreases*

*when tariffs are sufficiently high, $t_A \in (t_A^*, \infty)$, where the critical tariff rate, $t_A^*$, satisfies:*

$$t_A^* \pi_A^D\left(t_A^*\right) = \frac{\sigma}{\eta - \sigma}, \qquad \textit{with} \qquad \pi_A^D\left(t_A\right) = \left[(I-1)\left(d_A\left(1+t_A\right)\right)^{1-\eta} + 1\right]^{-1}.$$

Proposition 3 introduces two new terms to Equation (14), both which relate to changes in the share of worldwide expenditure in agriculture that is ultimately received by farmers, net of tariffs. We denote this pass-through rate by $(1 - h_A) = 1 - \frac{t_A}{1+t_A}\left(1 - \pi_A^D\right)$. The rate changes, first, because holding fixed $\frac{t_A}{1+t_A}$, a higher tariff shifts agricultural demand from foreign to domestic varieties, thereby raising the pass-through to farmers. Second, holding fixed the imported expenditure share, $\left(1 - \pi_A^D\right)$, a higher tariff increases the fraction collected by the government, $\frac{t_A}{1+t_A}$, lowering the pass-through to farmers. These two effects correspond to the second and third terms on the right-hand side of Equation (15). Together with the first term, which remains from Proposition 2, they indicate that the stock of land exhibits a U-shaped relationship w.r.t. agricultural tariff. In particular, when agricultural trade is sufficiently protected and there is enough complementarity between broad sectors of the economy, the first two terms dominate the last term in Equation (15), and a worldwide tariff reduction saves land.

Propositions 2 and 3 assume symmetric countries to highlight how structural change shapes the impact of trade costs on deforestation. In an asymmetric world, countries specialize according to their comparative advantage. Trade liberalization, therefore, can lead these countries to expand their agricultural frontier, which may reinforce or mitigate the above results. To shed light on this matter, we next illustrate the role of comparative advantage.

To state our next result in the clearest way, we consider a continuum of countries $i \in [0, 1]$ that have heterogenous productivities in agriculture and manufacturing, but are otherwise identical. In addition, we shut down the mechanism behind Proposition 2 by assuming that the elasticity of substitution between agriculture and manufacturing equals one ($\sigma = 1$) and the additional mechanism behind its tariff-based counterpart by assuming that goods within each sector are homogenous ($\eta \to \infty$). Without loss of generality, we order countries in decreasing order of comparative advantage in agriculture, i.e. $Z_{i,A}/Z_{i,M}$ decreases with $i$.

**Proposition 4.** *(Comparative and absolute advantage). Suppose goods within each sector are homogeneous and preferences are Cobb-Douglas (i.e., $\eta \to \infty$ and $\sigma = 1$). A reduction of trade costs that brings the world economy from autarky to free trade has the following consequences.*

*(i) Comparative advantage drives international specialization: There is a cutoff country $i^*$ such that all countries $i < i^*$ specialize in agriculture, and the rest specialize in manufac-*

*turing.*

*(ii) Comparative and absolute advantage in agriculture are aligned: If $Z_{i,M}$ decreases in $i$, so does $Z_{i,A}$ (as implied by our assumption that $Z_{i,A}/Z_{i,M}$ is decreasing in the country index $i$), meaning that comparative and absolute advantage align in agriculture but not in manufacturing. In this case, global forest area expands when moving to free trade.*

*(iii) Comparative and absolute advantage in agriculture are not aligned: If $Z_{i,A}$ increases in $i$, so does $Z_{i,M}$, meaning comparative and absolute advantage align in manufacturing but not in agriculture. In this case, global forest area shrinks when moving to free trade.*

Proposition 4 carries two main messages. The first message, in line with standard results from trade theory, is that comparative advantage is a key determinant of cross-country patterns of specialization.

The second message, to the best of our knowledge, is novel. It states that the correlation between absolute and comparative advantage determines whether trade increases global land use. In particular, when countries whose comparative advantage lies in agriculture also have an absolute advantage in agriculture (and an absolute disadvantage in manufacturing), agricultural production is undertaken by the most efficient agricultural producers in the free-trade equilibrium. This specialization pattern makes free trade a land-saving policy.

**Relation to Borlaug's Hypothesis** The above four propositions extend to an international environment the famed hypothesis put forward by Borlaug (2000), namely, that agricultural productivity growth in a closed economy protects forests because the demand for food is inelastic, and so is the derived demand for land. Our results show that, international trade can also act as a technological improvement that leads to a lower global demand for land, be it through reductions in trade costs—modeled as export-biased productivity increases or tariff reductions—or through efficiency gains brought about by the reorganization of production in the presence of comparative and absolute productivity differences across countries.

# 6 The Quantitative Model

Our quantitative model, which we will bring to data for quantitative policy analysis, extends the stylized model of Section 4 in five important dimensions, as outlined below. Appendix C presents the Quantitative Model in detail.

First, we incorporate a more detailed set of industries, denoted by $g$, consisting of a manufacturing industry, a service industry, and multiple agricultural industries, each differentiated into varieties by country of origin. Demand is structured in three CES tiers: the lower tier aggregates national varieties of each industry $g$ with substitution elasticity $\eta_g$; the

middle tier combines the agricultural industries into an agricultural composite with substitution elasticity $\kappa$; and the upper tier aggregates the composites of agriculture, manufacturing, and services into final consumption with substitution elasticity $\sigma$.

Second, we incorporate land, labor, and intermediate input use into Cobb-Douglas production technologies for each good $g$,

$$Q_{i,g} = Z_{i,g}\left(N_{i,g}^{\gamma_{i,g}} L_{i,g}^{1-\gamma_{i,g}}\right)^{\alpha_{i,g}} \left(M_{i,g}\right)^{1-\alpha_{i,g}},$$

where $Z_{i,g}$ is total factor productivity, $N_{i,g}$, $L_{i,g}$, and $M_{i,g}$ are, respectively, the use of labor, land, and intermediate inputs. The latter isin turn an aggregate over all industries using a tiered CES structure similar to that of final consumption, but with parameters specific to each using industry $g$. The parameter $\alpha_{i,g}$ measures the value added share, which is further divided between land and labor with shares $\gamma_{i,g}$ and $(1-\gamma_{i,g})$.

Third, we include an additional category of land, which we refer to as "fallow land". Specifically, the cleared land $L_i$ is divided into *usable* land $U_i$ and *fallow* land $O_i$, such that $L_i = U_i + O_i$ (and, as before, the country's total area consists of cleared land and forests, $H_i = L_i + F_i$). Accordingly, the usable land may depreciate to both forest area and fallow land.

Fourth, we allow the productivity in the land-clearing sector to depend on the available stock of forest and fallow land. Specifically, let $z_i$ denote the share of cleared land in total country area, $z_i \equiv L_i/H_i$, and $u_i \equiv U_i/L_i$ be the share of usable land within cleared land. Usable land is generated by converting forest ($F$) and fallow land ($O$)employing labor as an input. The corresponding production technologies are expressed as:

$$Q_{i,T}^{FU} = \underbrace{\zeta_{i,F}\left(1-z_i\right)^{\lambda}}_{\equiv J_i(z_i)}\left(N_{i,T}^{FU}\right)^{\gamma_F}, \qquad Q_{i,T}^{OU} = \underbrace{\zeta_{i,O}\left(z_i\left(1-u_i\right)\right)^{\lambda}}_{\equiv H_i(z_i(1-u_i))}\left(N_{i,T}^{OU}\right)^{\gamma_O}; \tag{16}$$

where $Q_{i,T}^{FU}$ and $Q_{i,T}^{OU}$ denote the usable land produced from forests and fallow land, and $N_{i,T}^{FU}$ and $N_{i,T}^{OU}$ denote the corresponding input uses. Total production and employment of the land-clearing sector are given by:

$$Q_{i,T} = Q_{i,T}^{FU} + Q_{i,T}^{OU}, \qquad N_{i,T} = N_{i,T}^{FU} + N_{i,T}^{OU}.$$

In our specification, $J_i(\cdot)$ and $H_i(\cdot)$ represent the productivity of converting forest and fallow land into usable land, and $\{\gamma_F, \gamma_O\}$ denote the output elasticities with respect to labor. Furthermore, $\{\zeta_{i,F}, \zeta_{i,O}\}$ are exogenous parameters and $\{\lambda\}$ is the elasticity of productivity $J_i(.)$ and $H_i(.)$ with respect to the available stock of forest and fallow land. The productivity

$J_i(.)$ is a decreasing function, reflecting the rising cost of deforestation as a shorthand for stricter policies, terrain variability, or greater distances to markets. Moreover, $J_i(1) = 0$ as no new land can be produced from forest if the entire forest is depleted. Similar properties apply to $H_i(\cdot)$. The representative land-clearing producer treats these productivities as fixed and does not internalize the effects of its production decisions on them.[14] Fifth, we introduce forward-looking workers à la Artuç et al. (2010) and Caliendo et al. (2019b). Workers can switch between agriculture, manufacturing, services and the land-clearing sector, conditional on receiving a move opportunity (which arrive with intensity $\psi$). Upon receiving an opportunity, they draw preference shocks from a Type-I extreme value distribution, with dispersion parameter $\nu$, and decide whether to move from sector $s$ to $s'$, incurring a moving cost $f^N_{i,ss'}$.

# 7 Taking the Model to Data

This section explains how we calibrate our model calibration and bring it to data. We disaggregate the world into the 40 countries or regional aggregates, as described in Section 3. We calibrate our model parameters in three steps. First, we calibrate the parameters related to the static equilibrium using data circa 2010. Second, we calibrate the labor-dynamics parameters based on previous literature. Third, we calibrate the technology in the land-producing sector so that the model matches reduced-form relationships between population growth and growth in agricultural land and forest area (which we presented as motivation in Section 3). We next explain each step. Table 2 summarizes our calibrated parameters.

## 7.1 Calibration of static equilibrium

In this first step we exploit the property that, in each time $t$, our model behaves like a static trade model with fixed employment of labor and land. We set the elasticity of substitution between agriculture, manufacturing and services, both in production and consumption, at $\sigma = \sigma^I = 0.5$, following Comin et al. (2021); the trade elasticity in each of the sectors, $\eta - 1 = 4$, following Simonovska and Waugh (2014), and the elasticity of substitution between crops at $\kappa = \kappa^I = 3$, following Costinot et al. (2016). For the cost share parameters, we use GTAP data to directly calibrate the share of value added in gross output $\{\alpha_{i,g}\}$ for all sectors and the labor share in value added $\{\gamma_{i,g}\}$ for agriculture. For non-agricultural sectors, the

[14] Our specification is rooted in the literature on renewables, e.g., Brander and Taylor (1997), that assumes $Q_{i,T} \propto (1 - z_i) N_{i,T}$. This corresponds to a special case of our specification where $J_i(z_i) = 1 - z_i$ and $\gamma_F = 1$, and the category of fallow land is assumed away.

Table 2: Parameter calibration

| Parameter | Value | Source |
|---|---|---|
| ***a. Technology and Preferences*** | | |
| Cost share of VA and labor, $\alpha_{i,g}, \gamma_{i,g}$ | – | GTAP, FAOSTAT |
| Elast. of substitution between goods | $\sigma = \sigma^I = 0.5$, $\kappa = \kappa^I = 3$ | Comin et al. (2021), Sotelo (2020) |
| Trade elasticity | $\eta = 5$ | Simonovska and Waugh (2014) |
| Trade costs and productivity | $d_{ni,g}, Z_{i,g}$ | Model inversion in 2010 |
| ***b. Technology for the production of new-land*** | | |
| Forest regrowth rate, $\delta_f$ | 0.5% | Brazil's data (Mapbiomas) |
| Fallow land regrowth rate, $\delta_o$ | 5.0% | Brazil's data (Mapbiomas) |
| $Q_{i,T}^{FU} = \zeta_{i,F} (1 - z_i)^{\lambda} \left(N_{i,T}^{FU}\right)^{\gamma_F}$, | $\zeta_{i,F}$ | $L_i$ and $F_i$ in 2010 to be at SS |
| | $\lambda = 0.90$ | Population and deforestation reg. |
| | $\gamma_T = 0.95$ | Population and deforestation reg. |
| $Q_{i,T}^{OU} = \zeta_{i,O} ((1 - u_i) z_i)^{\lambda} \left(N_{i,T}^{OU}\right)^{\gamma_O}$ | $\zeta_{i,O}$ | $L_i$ and $F_i$ in 2010 to be at SS |
| | $\lambda = 0.90$ | Population and deforestation reg. |
| | $\gamma_U = 0.9$ | Population and deforestation reg. |
| ***c. Dynamics of Labor and Land*** | | |
| Transition costs for labor, $f_{i,ss'}^N$ | $5 \cdot$ (annual income$_{US}$) | Artuc et al. (2010) in SS |
| Discount rate, $\rho$ | 0.05 | |
| T1EV dispersion for labor | $\nu = 0.5$ | Artuc et al. (2010) in SS |
| Arrival rates | $\psi = 1$ | – |

GTAP dataset does not provide information on the land share in value added. We, therefore, set the land share in value added $(1 - \gamma_{i,g})$ to match the global land share of urban areas.

Then, taking GTAP data from 2014 on international trade flows, gross output by industry and input-output matrices, we apply standard inversion methods to back out productivity shifters $\{Z_{i,g}\}$, and demand shifters $\left\{b_{ij,g}, b_{i,s}, b_{i,k}, b_{i,gs}^I, b_{i,gg'}^I\right\}$ given trade costs $\{d_{ij,g}\}$, which we explain how we parameterize next.

**Trade Costs.** Our calibration of trade costs distinguishes the components of trade costs that are associated with policy barriers and transportation costs. We model the price of taking a good from $i$ to destination $j$ as

$$p_{ij,g} = \left(p_{i,g} d_{ij,g}^{ice} + p_{i,S} d_{ij,g}\right) t_{ij,g}^{ice} \left(1 + t_{ij,g}\right)$$

where $d_{ij,g}^{ice}$ is an iceberg trade cost unrelated to policy, $d_{ij,g}$ is a transportation cost paid in terms of the final good of the domestic service sector $(p_{i,s})$, $t_{ij,g}^{ice}$ is an iceberg policy related cost, and $t_{ij,g}$ is the tariff rates. Our approach follows the literature: We estimate gravity models, extract the residuals from such regressions, and then exploit data on policy variables, including tariffs, free trade agreements, and import fees, to generate tariff equivalent measures of these policies — see for example Nath (2020). Appendix D.1 describes in detail our approach.

## 7.2 Calibration of labor dynamics

In this second step, we set the sectoral labor supply elasticity at $1/\nu = 2$ and the labor mobility costs, $f^N_{ss'} = f^N$, in line with previous work on labor mobility.[15] We also set arrival rates of move opportunities $\psi$ to 1.[16]

## 7.3 Calibration of the land dynamics

In the third and final step, our calibration of the parameters in the land-producing sector follows a nested approach. In the inner nest, given values of the elasticities $\{\lambda, \gamma_F, \gamma_O\}$, we recover the productivity shifters $\{\zeta_{i,F}, \zeta_{i,O}\}$ such that the model's steady state values of agricultural land, fallow land, and forest area match their observed values in the initial year of our sample.[17] In the outer nest, in the spirit of indirect inference, we search for the values of the elasticities $\{\lambda, \gamma_F, \gamma_O\}$ so that our model mimics the reduced-form dynamic responses of deforestation and land use to population shocks. Specifically, after calibrating $\{\zeta_{i,F}, \zeta_{i,O}\}$, (i) we shock the model with the UN population growth projection until 2100, and (ii) using these simulated data, we run a set of regressions along the lines of equation (1) in Empirical Pattern 4 but focusing on the dynamics of the shock:

$$\underbrace{\log\left(y_{i,t}\right) - \log\left(y_{i,1990}\right)}_{\text{different time lags}} = \beta_0 + \beta^y_t \underbrace{\left[\log\left(\text{Pop}_{i,2020}\right) - \log\left(\text{Pop}_{i,1990}\right)\right]}_{\text{30 years lag}} + \epsilon_i,$$

where we chose $t = \{2000, 2010, 2020\}$ allowing for the dependent variables to vary at 10, 20, and 30 year horizons, and $y_{i,t}$ is either forest area or agricultural land area. The different coefficients $\beta^y_t$ across time horizons $t$ allow us to capture the total response of agricultural land and forests to the shock, as well as how quickly this response unfolds. The distinction between the two allows us to separate $\{\gamma_F, \gamma_O\}$ from $\lambda$, as we explain below.

Stacking all the coefficients $\{\beta^y_t\}_{t,y}$ in a vector $\beta$, we search for values of $\{\lambda, \gamma_F, \gamma_O\}$ to minimize

$$\left(\beta^{(\text{data})} - \beta^{(\text{model})}\right)\left(\beta^{(\text{data})} - \beta^{(\text{model})}\right)'$$

where $\beta^{(\text{data})}$ is the vector of parameters estimated using the actual data, and $\beta^{(\text{model})}$ is the

[15] Caliendo et al. (2019b) report that the yearly equivalent of their labor elasticity equals our choice of $1/\nu = 2$. For the labor mobility cost, $f^N$, we follow McLaren (2017) who reports estimates of about five times yearly real income, which we target for US service workers in the steady state.

[16] Our calibration approach imposes that the stock of cleared land in the initial year equals its steady-state value in the absence of any changes in fundamentals. The stock of workers in each sector, however, is not constrained and does evolve from the starting point to the steady state. Appendix Figure H.9 documents this aspect of our calibration.

[17] Appendix Figure H.2 show the allocation of land between agricultural land, fallow land and forest area in our data.

vector of parameters estimated using model-generated data.

Our procedure can separately pin down the three above elasticity parameters. First, in the data fallow land accounts for a sizable share of a country area and, it is a source of expansion of agricultural land (recall Appendix Figure H.2). Therefore, in response to population growth, agricultural land may expand partly at the expense of forests and partly by converting fallow land. This distinction separately identifies the parameters that govern the expansion from forest, $\gamma_F$, from those that control the expansion from fallow land, $\gamma_O$. Second, our regressions reveal that land expansions respond differently at various time horizons to a 30-year change in population, capturing the strength of persistence built-in the land conversion function via $J_i$ and $H_i$. This variation helps us pin down the labor elasticity separately from the initial condition elasticity, i.e., $\lambda$. Higher labor elasticities scale up the overall deforestation responses, whereas higher area elasticities, $\lambda$ reduce future land-clearing productivity, and makes short-run responses relatively larger.

## 7.4 Model validation

Before moving on to the quantitative analysis, we briefly discuss four exercises that validate the performance of our model (See Appendix E). First, we show that the fallow land module is essential to match the reduced-form evidence on the impact of population on agricultural land. Without fallow land as an additional source of agricultural land expansion, the model substantially underestimates the response of cleared land to population growth (Appendix Figure H.6).

Second, although our calibration only targets the impact of own population growth, the model closely reproduces the reduced-form impact of foreign population growth, as documented in Empirical Pattern 4 (Appendix Table H.8). This finding means that the role of international trade as a transmission mechanism of land pressures across countries—a central mechanism in our paper—is aligned in the quantitative model and our reduced-form results.

Third, the calibrated values of the forest conversion productivity shifters, $\zeta_{i,F}$, do a good job in capturing variation in institutional regulations protecting forest across countries (Appendix Figure H.7). That is, in the absence of a richer formulation of institutional differences across countries, the calibrated values of productivity of land-clearing sector reflect real-world differences in the ease to deforest.

Fourth, the model-implied yields correlate well with actual data on yields, which we did not use in calibration (Appendix Figure H.8). This means that our calibrated model captures actual cross-country differences in the productivity and land intensity of agriculture, a sector that is key to studying deforestation.

Overall, our calibrated model replicates key features of the data (including several untargeted moments) on trade, land productivity, forest protection, and deforestation dynamics, making it a useful laboratory to study the impact of trade barriers on forests.

# 8 Counterfactual Analysis

In this section, we examine the quantitative impacts of reducing agricultural trade barriers on deforestation and welfare around the world. We focus on the consequences of eliminating agricultural import tariffs, as this counterfactual scenario is firmly grounded on policy considerations.[18] We present results, first, starting from a baseline without population growth, and then incorporate population growth forecasts up to the year 2010. We close the section by providing a cost-benefit analysis centered around the gains from trade from tariff elimination and the $CO_2$ cost of deforestation.

## 8.1 Removing agricultural import tariffs

We contrast two counterfactual scenarios, both of them involving the elimination of agricultural tariffs. In the first scenario, we only eliminate the agricultural tariffs charged by every region on Brazilian exports. In the second, we simulate a multilateral agreement in which all countries remove their agricultural tariffs. Besides being important in their own right, these policy scenarios allow us to highlight the importance of general equilibrium adjustments, via structural change and comparative advantage (as fleshed out in Propositions 1 through 4). Additionally, we provide a cost-and-benefit analysis in which we account for the climate costs of deforestation.

### 8.1.1 The path of forests

We begin by reporting the frontier of cleared land in the business as usual (BAU) scenario—which is the baseline outcome of our model where no policy change or any other shock is introduced. Panel (a) in Figure 6 shows this path for select countries. As a consequence of our approach to calibration, the land frontier remains almost constant across countries and globally, in this scenario lacking any shocks.[19]

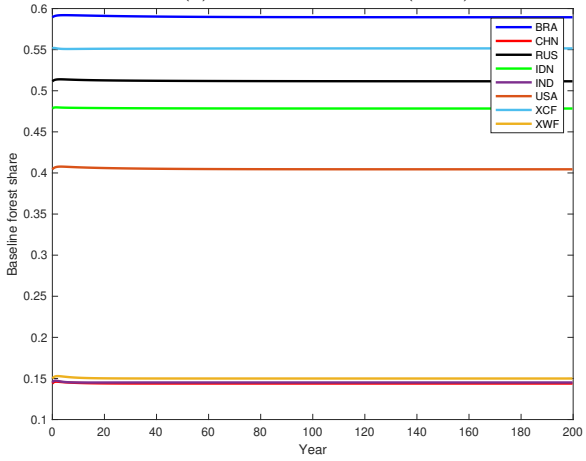
Figure 6 displays the percentage point changes in forest share relative to the BAU, both at the level of the world and for select countries. As shown in Panel (b), removing tariffs

[18] For comparison purposes, we collect analogous impacts of reducing iceberg trade costs in Appendix F.

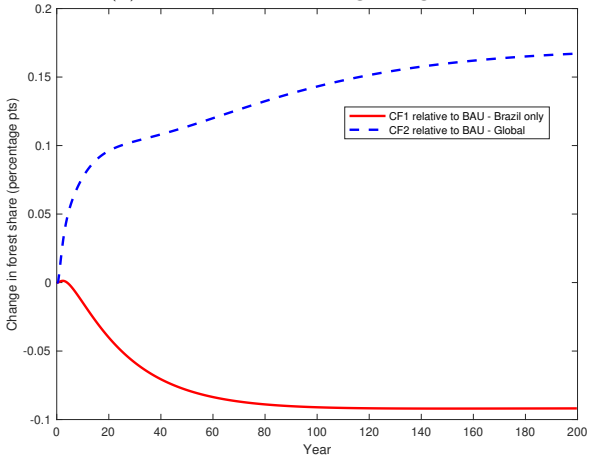
[19] We emphasize that this baseline is not a forecast based on our model. In our baseline scenario, productivity, population, and land remain constant over time, while one would need to know their future paths to forecast the future of forests.

Figure 6: Multilateral vs Unilateral Tariff Elimination: Change in Forest Area Relative to Baseline (Global and Selected Countries)

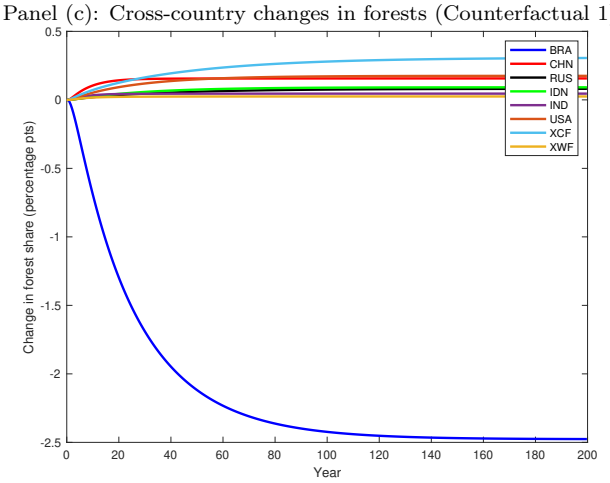
Panel (a): Business as usual (BAU)



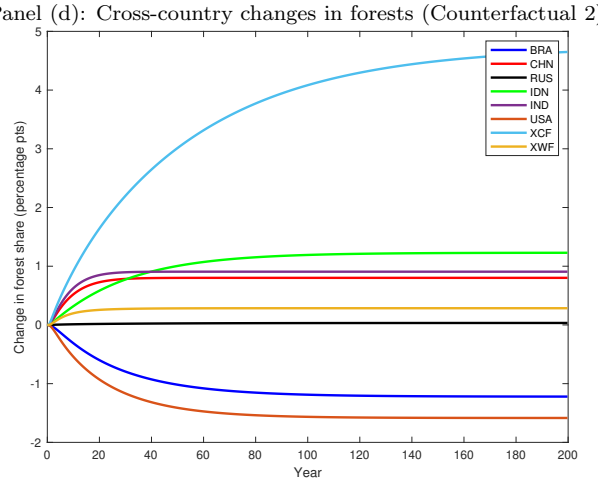

Panel (b): Counterfactual changes in global forests




Panel (c): Cross-country changes in forests (Counterfactual 1)




Panel (d): Cross-country changes in forests (Counterfactual 2)




**Notes**: Panel (b), (c) and (d) shows at time $t$ the difference in forest share in the counterfactual relative to BAU shown in Panel (a).

only on Brazilian agricultural exports leads to a reduction in global forest area. In contrast, eliminating agricultural tariffs worldwide results in an expansion of global forest area.

Recall from Proposition 3 that a global reduction in tariffs has an ambiguous effect on global forest area. Our quantitative findings show that the land-saving forces, primarily driven by structural change, dominate the negative, direct effect of tariff reductions on forest area.[20]

Panels (c) and (d) show the heterogeneous responses of forests in a selected set of countries. In the first policy scenario (Brazil only), the forest area falls sharply in Brazil whereas it increases elsewhere. The forest loss in Brazil amounts to 1 p.p. after 14 years, 2 p.p. after 42 years, and 2.5 p.p. at the steady state—the reduction in tariff equals 8.6 p.p., which gives an implied elasticity of tariff with respect to forest area equals -0.04.[21] The implied steady-state "forest leakage", i.e., the eventual forest gain in the rest of the world for each unit of forest loss in Brazil equals about 50%, but the leakage can be three times larger in the short-run, taking about 30 years to converge to its steady-state value (see Appendix Figure H.12).

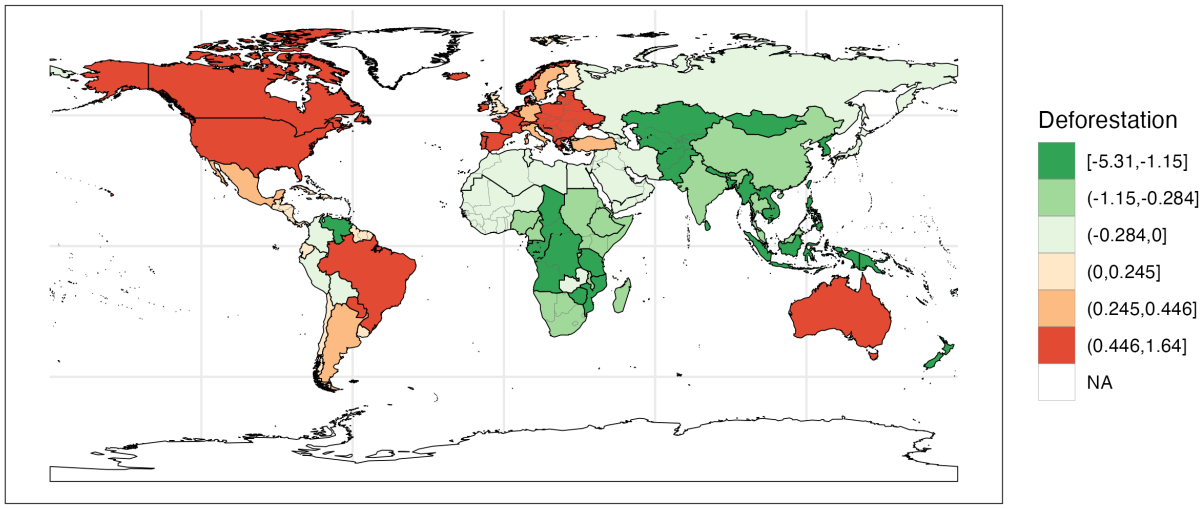
Panel (d) reports analogous results for the second policy scenario (multilateral tariff liberalization). The forest area expands in Central Africa (labeled as "XCF") and South East Asia, whereas North America, Europe, and Brazil experience relatively large rates of deforestation. Although structural change leads to aggregate reforestation, countries that have a comparative advantage in agriculture or that are geographically well positioned to serve economies that specialize in non-agriculture, take advantage of the tariff reduction by expanding their agricultural sector at the expense of their forests.

To illustrate the geography of deforestation in response to multilateral agricultural tariff removals, Figure 7 shows the steady-state changes in forest area (as a share of country area) on a global map. Forest area increases in all tropical countries except Brazil, which has a particularly strong comparative advantage in agriculture. For a similar reason, boreal forests tend to experience significant forest loss. This pattern stands in sharp contrast to the actual deforestation of recent decades, which was widespread across tropical countries and less prevalent in boreal regions.

[20] Analogous reductions in iceberg trade costs, instead of import tariffs, result in a larger increase in global forest area (see Appendix F). This quantitative finding is consistent with Propositions 2 and 3, which highlight the attenuating effect of tariff reductions compared to iceberg trade cost reductions.

[21] The share of forest in percentage points in Brazil in the baseline is 58, whereas the forest reduction is 2.5 percentage points. Tariff reduces by 100 percent. That gives $-0.04 = (2.5/58) / (-1)$

Figure 7: The Impact of Eliminating Tariffs on Forests Across the World



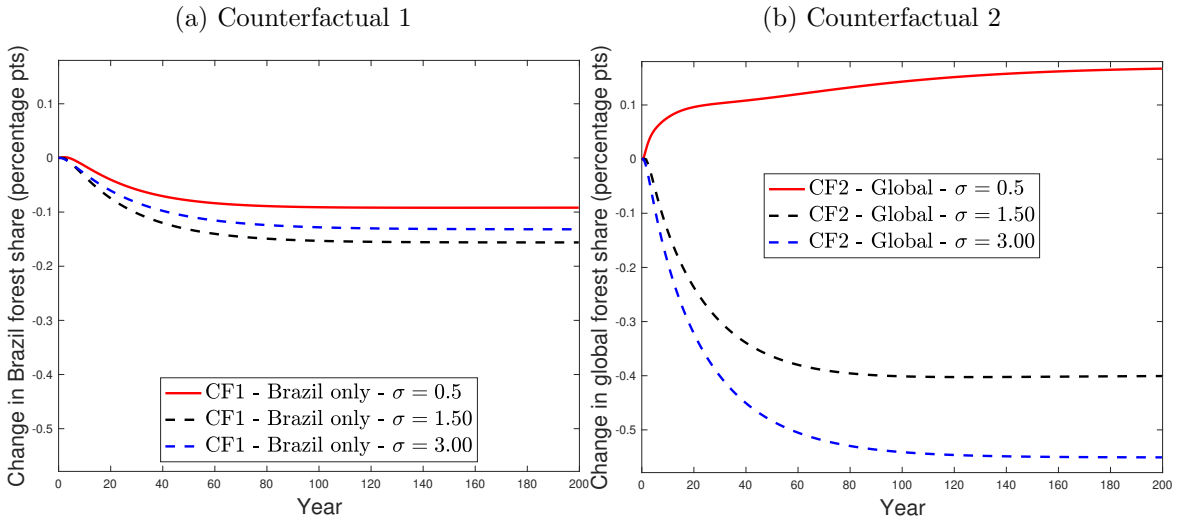

**Notes**: This figure shows the changes in forest area in the steady state following a multilateral reduction in global agricultural tariffs. Bold lines indicate the 40 regions analyzed in the paper, while thinner lines denote country-level boundaries.

### 8.1.2 The roles of structural change and comparative advantage

We examine the quantitative importance of structural change and comparative advantage as adjustment mechanisms in response to the multilateral trade liberalization of agriculture.

**Structural Change** To illustrate the contribution of structural change, in Figure 8 we display the counterfactual path of forests under three values of the sectoral elasticity of substitution, $\sigma \in \{0.5, 1.5, 3.0\}$. Increasing $\sigma$ limits the scope of structural change for reducing land demand, by muting the complementarity and turning it into higher substitutability between the agriculture and non-agriculture sectors. The figure demonstrates that a larger value of $\sigma$ reverts the path of global forest area in Counterfactual #2 but does not qualitatively change that of Counterfactual #1. These quantitative results show that the relevant elasticity of demand for agricultural goods depends on the geographic scope of trade-cost shock. For an individual exporter, demand is largely elastic, due to trade; but in the global economy, demand is largely inelastic, due to structural change.

Figure 8: The role of the elasticity of substitution, $\sigma$




**Comparative Advantage** To explore quantitatively the role of comparative advantage, Figure 9a relates the comparative advantage in agriculture relative to manufacturing as measured in the model (on the x-axis) and the counterfactual change in the forest share in the steady state (on the y-axis) for our main specification at $\sigma = 0.5$. Comparative advantage governs the cross-sectional responses: Upon a reduction in trade costs, countries with a comparative advantage in agriculture take advantage of the new trade opportunities and, to expand their agricultural sector, they clear their forests.

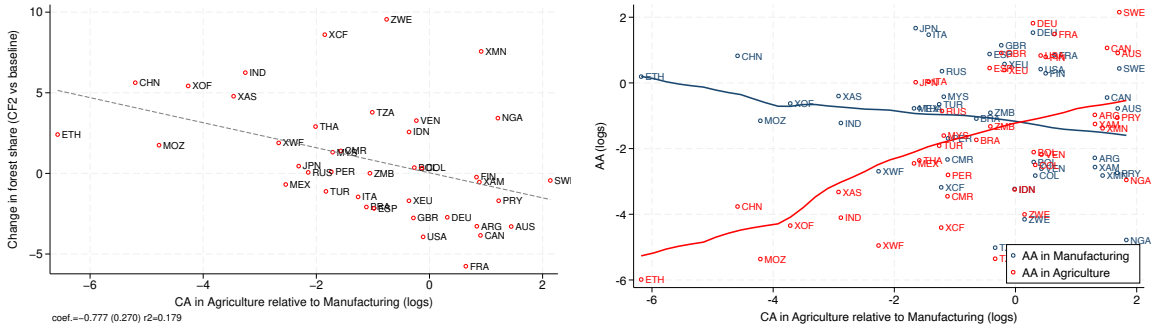
In addition, Figure 9b shows that across countries relative productivity in agriculture, $Z_{i,A}/Z_{i,M}$, is positively correlated with absolute agricultural productivity, $Z_{i,A}$, while it is only weakly correlated with absolute manufacturing productivity, $Z_{i,M}$, (both recovered via model inversion), which means that trade reallocates agricultural production to the most efficient agricultural producers. Through the lens of Proposition 4, the figure suggests that expanding agricultural trade leads to global land savings.[22]

[22]Note that $Z_{i,A}$ represents land productivity in our Stylized Model (hence, in Proposition 4) whereas it corresponds to total factor productivity (TFP) in our quantitative model (hence, for the reported result). Therefore, connecting to Proposition 4 requires a qualification: any positive relationship between TFP-based measures of comparative and absolute advantage in agriculture must be adjusted to account for differences in agricultural land intensity across countries.

Figure 9: The Role of Comparative Advantage

(a) Deforestation in the cross-section

(b) Absolute and Comparative Advantage in Agriculture




**Notes**: Panel (a) shows the correlation between the comparative advantage of a country in agriculture (average of implied TFPs across goods) relative to manufacturing and the change in forest area in steady state between BAU and a multilateral reduction in global agricultural tariffs. Panel (b) shows the correlation between comparative and absolute advantage in agriculture, relative to manufacturing.

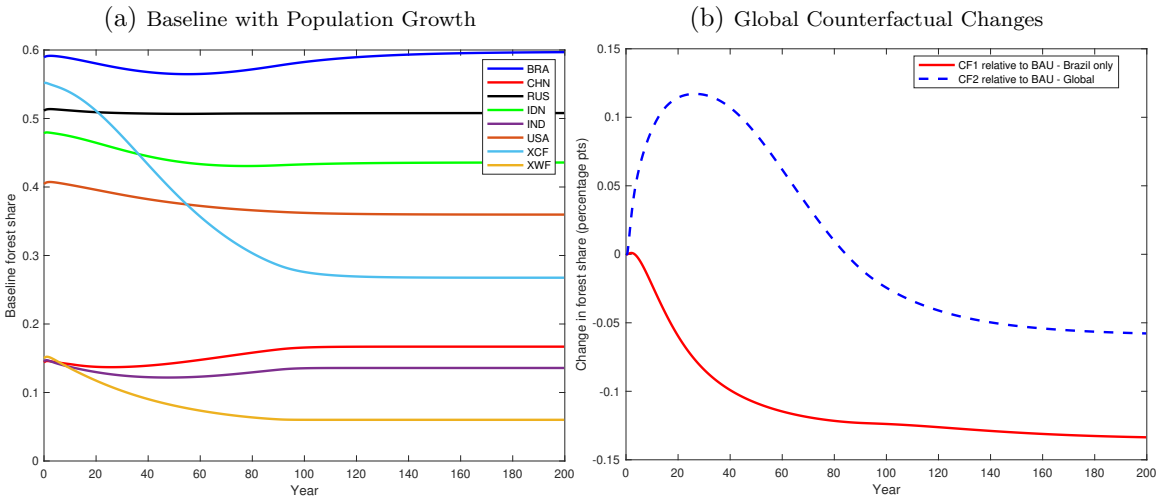
## 8.2 Incorporating population growth

This section expands our analysis in two directions. First, we examine the impact of population growth on deforestation, by focusing on an alternative business-as-usual scenario that incorporates UN population growth projections until 2100. Average population growth will be large and uneven across countries: The average will be 35 percent, and it will range from population reductions in Japan to more than 300 percent increases in parts of Africa, where large forests areas remain untouched. Since population growth, as we discuss below, is a key determinant of pressures on land, understanding this new scenario is crucial. Second, we reevaluate the scope of trade policy to mitigate deforestation and its associated costs, under this new BAU scenario, showing that although its impact on global forests is small, it induces important reallocation across countries.

Panel (a) of Figure 10 displays our new BAU scenario. There are large increases in the amount of cleared land (and hence, reductions in forest) in countries in which population growth is projected to be largest. Countries such as Brazil and Indonesia, where population growth is smaller, experience early but moderate expansion in their cleared land, which is then partially reverted as countries with higher population growth develop new land to serve their growing domestic demand for agricultural goods. This is in line with the theoretical predictions of our model, which suggest that population size is one of the key drivers of land stock in equilibrium.[23] Appendix Figure H.13 shows, for our whole sample, that countries

[23]Consider, for example, Appendix Equation B.13, which implies that the elasticity of land stock to population is equal to 1, in the context of a collection of symmetric economies. In our quantitative model, these effects are modulated by the curvature of the function $J(.)$ and the ensuing changes in factor abundance,

Figure 10: The Role of Population Growth




with larger population growth experience larger deforestation (steady-state relative to 2010) in the new BAU. Table H.3 in the Appendix reports the corresponding values.

Panel (b) of Figure 10 shows that, relative to this new BAU, our counterfactual scenarios remain qualitatively similar to those without population growth: Global forest area shrinks with the elimination of tariffs faced by Brazil, whereas a global tariff elimination leads to much smaller, albeit slightly positive, global deforestation. That trade policy has limited scope for curbing global deforestation reflects, in part, the larger importance of population growth as a driver of deforestation. Equally important for our results, however, in the multilateral tariff elimination scenario, there is substantial reallocation of land pressure—and, therefore, of reforestation—across countries. As we show below, this reallocation yields a reduction in the deforestation costs of the policy (relative to a scenario without population growth), because on average forests with higher carbon content are protected, even if global forest cover decreases marginally.

Our results show the different impacts on forest area globally and across countries in response to trade costs, highlighting the importance of general-equilibrium forces, such as structural change and comparative advantage. In particular, starting from both our BAU scenarios with and without population, our simulations show that tariff elimination induces substantial reallocation of deforestation across countries (see Figure 6, Panel (d) and Appendix Figure H.11, Panel (b)). Together with the substantial heterogeneity in carbon content of forests we have documented (Figure H.1), such reallocation suggests that the welfare costs of tariff elimination will depend on the details of which countries end up deforesting more. We turn now to an evaluation of the costs of deforestation, comparing them with the

which in turn imply changes in marginal costs.

welfare gains of trade liberalization implied in these scenarios.

## 8.3 Carbon heterogeneity, dynamics, and reforestation.

We now provide two alternative measures to evaluate the benefits and costs of elminating agricultural tariffs, and the deforestation associated with doing so. First, we measure the impact of tariff reductions on the $CO_2$ emissions from deforestation, following the guidelines used by the IPCC to calculate the climate costs from deforestation-related $CO_2$ emissions.[24] Each hectare of forest loss per country and year corresponds to an implied $CO_2$ emission released to the climate.[25] We then give a value to the global level of emissions produced at any point in time using a social cost of $CO_2$ of 200 \$/tC or 1000\$/tc, and bring those flows to present value using a discount rate of 5%.[26] To provide a sense of the magnitude of these costs, we present them as a fraction of total US GDP in 2010.

Our second measure compares the welfare gains from trade liberalization against the welfare costs of carbon, to produce a net welfare gains measure. The net gains are computed as the change in the present discounted value of real consumption, augmented by the change in the social cost of deforestation-related carbon emissions.[27]

Table 3 presents both measures, for the world as a whole, across several specifications, for both Counterfactuals 1 and 2. As a starting point, Column (1) evaluates the tariff reductions with a zero cost of carbon. This scenario simply elicits the welfare gains from trade liberalization, which are larger in Counterfactual 2, as it involves a multilateral liberalization. Column (2) repeats the calculation, now valuing carbon at a price of 200 \$/tC. Both counterfactuals involve additional deforestation relative to the BAU in some countries (even

[24]Our evaluation does not incorporate other costs associated with deforestation. These other costs stem from the loss of wildlife endemic to each forest, the change in landscape that increases the likelihood of flooding, the amenity value of forests, and desertification. Additionally, we abstract away from the costs associated with reforestation such as the adverse health effects of pollen.

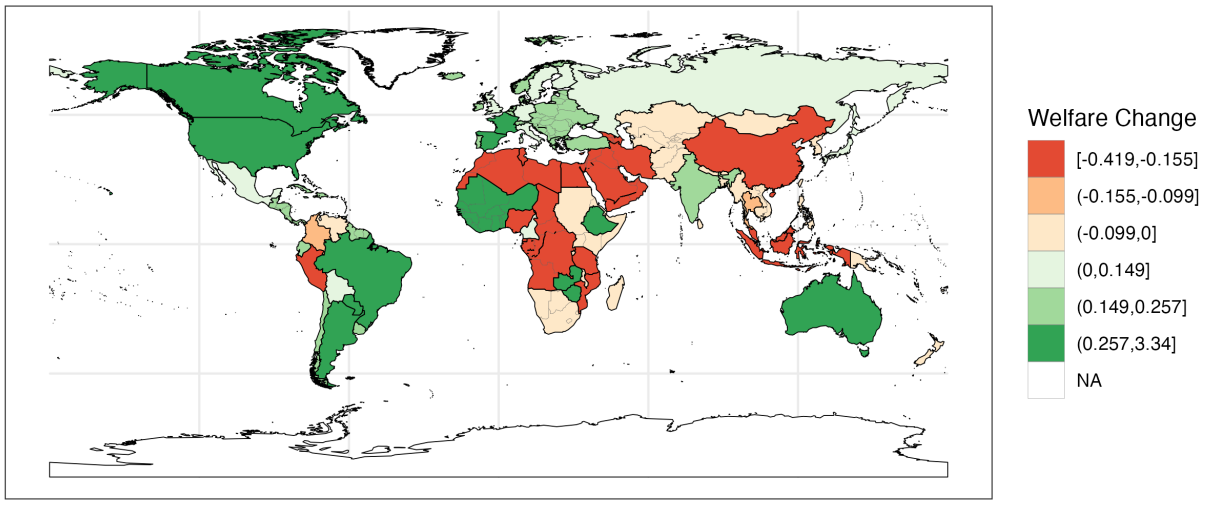
[25]Specifically, following the guidelines described in Tubiello et al. (2020), we use the following equation to compute $CO_2$ emissions from deforestation: $NFC_{i,t} = -\frac{B_{i,t-1}}{A_{i,t-1}} \min\left[A_{i,t} - A_{t,t-1}, 0\right] \frac{44}{12}$,where $NFC_{i,t}$ is the net deforestation, expressed in tonnes of $CO_2$. The term $\frac{44}{12}$ converts $C$ to $CO_2$—it is the ratio of the molecular weight of carbon dioxide, which equals 44, to that of carbon, which equals 12. Note that this is a somewhat pessimistic approach since (i) it assumes when a hectare of forest is lost, all the carbon previously stored in that hectare is immediately released, and (ii) it does not account for reforestation.

[26]The value of 200 \$/tC is consistent with the the latest release of the United States Environmental Protection Agency (EPA)'s Final Report on the Social Cost of Greenhouse Gas. The value of 1000\$/tc is in line with results from Bilal and Känzig (2024).

[27]We specify the global climate-adjusted welfare as $V - \varphi Z$, where $V$ represents world real consumption, $Z$ denotes global emissions, and $\varphi$ measures the marginal disutility per unit of global emissions. Assuming a constant marginal disutility allows for a simple calibration of the social cost of carbon, and a transparent calculation of climate-adjusted welfare gains for each scenario of deforestation-related changes to emissions. See Appendix G for details.

if in net world forests grow), which means that the environmental costs are positive (and up to 8 % of US GDP in 2010). Although large, these environmental costs are overcome by the benefits of trade liberalization, yielding a net positive in the case of a multilateral trade liberalization.. Figure 11 shows that average gains from trade come with substantial heterogeneity across our 40 regions. In fact, the gains from trade correlate positively with the deforestation response to the policy change, highlighting that while a global elimination of agricultural tariffs brings aggregate gains, it also entails potentially difficult political economy problems.[28]

Figure 11: The Gains from Trade from Eliminating Tariffs Across the World




We consider two additional scenarios, both of which suggest that a multilateral liberalization brings larger benefits than environmental costs. In Column (3) we consider the impacts of liberalizations starting from the BAU that includes population growth (still pricing carbon at 200 $/tC). Note first that the environmental costs of a multilateral reduction become smaller now, relative to a BAU without population growth, even if global forest cover decreases (as shown in Figure 10). The reason is that, with population growth, deforestation occurs in the BAU in countries that are relatively forest intensive, such as those in Africa. A trade liberalization in this case shifts deforestation away from these countries, lowering its environmental cost. In addition, the net welfare gains remain positive. Finally, Column (4) scales up the cost of carbon to 1000 $/tC. We consider this an upper bound on the environmental costs that could ensue if if the damages from emissions become larger in the

[28]In our model, when a country scales back its agricultural sector, its stock of land shrinks, resulting in lower real GDP per worker.

future. Our main conclusions in this scenario remain, although the environmental costs are substantial (at 18.5 percent of US GDP in Counterfactual 1).

**Remarks and robustness** Although these simulations suggest that, across several scenarios, the net impact of multilateral liberalizations on global welfare is positive, we emphasize that our approach brings broader messages. One of our key messages is the role of general equilibrium forces in determining the impact of deforestation. To shore up this message, we recompute our counterfactual scenarios setting $\sigma = 1.5$, which changes the direction in which structural change operates (See Propositions 2 and 3). Doing so increases the total amount of deforestation and its environmental cost in response to multilateral trade liberalizations, and increases also the environmental cost.[29] We also consider non-homothetic preferences, using the formulation from Comin et al. (2021), and find little change in our quantitative findings. Results are reported in Appendix Table H.13.

A second message is that, given our calibration of the structural change and comparative advantage forces, tariff hikes lead to worse global outcomes, especially when applied broadly. As shown in Appendix Table H.9, Panel B, in our main calibration a 10x increase in tariff rates worldwide leads to net welfare losses, across all carbon cost and population growth scenarios.

Third, a general feature of our simulations is that the responses of forests vary across countries, with some of them often regrowing their forests. On the one hand, such heterogeneity suggests that to obtain a full picture of the evaluation of a policy, one must incorporate the responses of all countries involved (as we do in our calculations). On the other hand, it also suggests that the details of the valuation of forests will have a bearing on our final calculations. Our main specification calculates the costs of deforestation under a model of partial carbon sequestration of 30 percent, which means that regrowing forest captures carbon from the atmosphere, but at a lower rate than is lost from deforestation.[30] The guidelines used by the IPCC, however, ignore the possibility of carbon sequestration from new growing forests. Appendix Table H.10 shows our main results assuming that regrowing forests do not recapture carbon, and confirms that although the associated environmental costs are higher, the average gains from eliminating agricultural tariffs remain larger than the costs. Finally, Appendix Table H.12 reports the environmental costs and welfare gains when we adopt different assumptions on the discount rate of agents. Different assumptions

[29]The message on the welfare gains in this case is less clear, and varies across specification. The reason is that the while quantity responses of the agricultural sector are larger, so is the potential for gains from buying cheaper agricultural goods.

[30]Specifically, we assume that forest regrowth sequestrate carbon from the atmosphere at a 30 percent rate, which means that, relative to the initial carbon stock per hectare in the data, every hectare of forest recovered absorbs 30 percent of that initial carbon density.

make the environmental costs orders of magnitude different, since much of the deforestation process takes many years to unfold.

Table 3: Costs and Benefits of Eliminating Agricultural Tariffs

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| *Panel A: Brazil* | | | | |
| Environmental Costs (as fraction of US GDP) | 0.000 | 1.925 | 2.772 | 13.860 |
| Welfare gains (percentual change) | -0.090 | -0.100 | 0.000 | -0.052 |
| *Panel B: All countries ($\sigma = 0.5$)* | | | | |
| Environmental Costs (as fraction of US GDP) | 0.000 | 5.915 | 2.536 | 12.679 |
| Welfare gains (percentual change) | 0.131 | 0.101 | 0.167 | 0.122 |
| *Panel C: All countries ($\sigma = 1.5$)* | | | | |
| Environmental Costs (as fraction of US GDP) | 0.000 | 35.594 | 39.853 | 199.266 |
| Welfare gains (percentual change) | 1.267 | 1.150 | -0.090 | -0.561 |
| *Economic Assumptions* | | | | |
| - SCC = 0 | Y | - | - | - |
| - SCC = 200 | - | Y | Y | - |
| - SCC = 1000 | - | - | - | Y |
| - Population Growth | - | - | Y | Y |

**Notes**: This table shows the present value of the gains in real GDP and the present value of the costs in terms of carbon emissions of different policy counterfactuals using different assumptions on the costs of carbon emissions from deforestation. Column (1) and (2) compute such gains and costs by comparing the counterfactual scenario with the baseline trajectory of GDP and environmental costs in a scenario with no population growth. Columns (3) and (4) proceeds analogously using the baseline scenario in which there is population growth. To compute costs and gains, we weight countries based on their population.

# 9 Conclusions

Global deforestation drives carbon emissions and reduces biodiversity, which poses an important challenge for policy. Meanwhile, the potential for agricultural trade liberalizations raises the concern over the impact on deforestation. We have developed a framework to study—analytically and quantitatively—the deforestation impact of trade policy. The key insight of our paper is that in a trading world, structural change and comparative advantage interact to determine aggregate land use and how it is distributed across countries. Our results provide a new rationale for international cooperation in trade policy, by showing that multilateral trade liberalization can help circumvent trade offs between the gains from trade and preservation of the forests.

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# A Details on Data

**Forest Area.** Our main source of information on forest area comes from FAO-FRA (FAO Global Forest Resources Assessment), which is based on questionnaires that are submitted to the agricultural agencies of every country. Since the 1990s, these data have been compared with measures of forest cover identified from satellite imagery such as Landsat (MacDicken, 2015). Nowadays, about 70% of national forest inventories utilize remote sensing to validate at least some portion of the inventory.

The FRA data are available for the years of 1990, 2000, 2005, 2010, 2015 and 2020 and they provide different measures of forest area.[31] When available, we use information on the naturally regenerating forest, which excludes forest area related to industrial forests planted for the production of, for example, paper. Our statistics sometimes diverge slightly from the ones reported by FAO-FRA since they report net deforestation, which incorporates both forest regeneration and forest plantation and we exclude the second from our measure. For our empirical analysis in Section 3, we grouped islands (e.g., Virgin Islands and Gibraltar), small regions (e.g., as Monaco and the Vatican), and countries with negligible forest areas (e.g., Kuwait and Bahrain) into larger regions. Appendix Table H.4 documents summary statistics for all countries in our final data.

In addition to FRA, another increasingly used source of data comes from Hansen et al. (2013b), who measures global deforestation using satellite imagery at a high spatial resolution (30 meters). Different from the data from FAO-FRA, which is designed to measure forest area based on land use classifications, the data from Hansen et al. (2013b) measures forest area based on forest cover. As such, Hansen et al. (2013b) tends to capture transitory changes in forest area such as the ones related to fires and insect outbreaks, even when there are no changes in land use, which is the concept that we use in the formulation of our model.[32][33]

[31] The main definition of forest is any land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds on site—it does not include land that is predominantly under agricultural or urban land use. The data, however, also provides information on planted trees and naturally regenerating forest.

[32] As identified by Curtis et al. (2018), about 23% of global forest disturbances between 2001 and 2015 can be attributed to wildfires. This driver of forest loss has been the dominant one in Russia, Australia and New Zealand. In contrast, agricultural-related activities have been the main source of deforestation in South America, Africa and Southeast Asia. Urbanization accounts for a minimal share of the changes in forest area. In addition, as discussed in Keenan et al. (2015), since Hansen et al. (2013b) use difference methodologies to measure deforestation and reforestation, one must interpret net changes in forest area coming from Hansen et al. (2013b) with caution.

[33] Moreover,Coulston et al. (2014) found that measures of forest land and forest land cover in the south-eastern USA are poorly correlated and suggest that these measures are better correlated in tropical areas. Recent papers that exploit the high-resolution data from Hansen et al. (2013b) to identify the reduced-form impact of different policies on deforestation are unlikely to be affected by these considerations about the limitations of satellite based data sets, since they focus on deforestation in tropical countries.

**Agricultural Area and Fallow Land.** We construct the total area in cropland using data from FAOSTAT on total harvested area. These data do not provide, however, information on the total area dedicated to cattle grazing. To recover that information, we multiply data on the total cattle stock by a simple conversion rate of 0.75 hectares per cattle, which we define as the pasture land.[34] Based on that information, we then compute the fallow land as the residual land, that is, the total land in the country minus the artificial surface, the watersurface, the forest area, the cropland, and the pasture land.

To compute the share of forest in a country, we use the total area of the country, as reported by FRA, which already excludes the water surface in a country. In addition, using data from FAOSTAT on land cover, we remove from the total area of the country the snow cover and the barren land—which includes desert areas. We refer to this resulting variable as "country area".

**Trade Costs.** To calibrate the trade costs generated by policy, we use data on (i) tariffs from the World Bank World Development Indicators—specifically, we use the simple unweighted average of the effectively applied rates for all products subject to tariffs—, (ii) import fees and days to import from the World Bank Doing Business, and (iii) trade agreements from CEPII Gravity Database—we take the country-destination specific free trade agreement indicator for year 2010, which is the dummy variable that takes the value of 1 if the country pair is engaged in a regional trade agreement. For the trade costs generated by geography, we use data from CEPII, which includes data on contiguity, distance, common language, and colonial relationships.

**Carbon Stock.** Our main data source for the carbon stock of forests is FAO-FRA. FRA contains data on six carbon pools: above- and below-ground carbon stock, dead wood, litter, soil, organic carbon, and harvested wood products. In our simplest exercise, we use the information on above- below-ground carbon stock, which is the typical approach when measuring the CO2 emissions from deforestation (IPCC, 2006). The definition of carbon in above-ground biomass is all carbon in living biomass above the soil, including stems, stumps, branches, bark, seeds, and foliage, whereas the definition of carbon in below-ground biomass is all carbon in all biomass of live roots (fine roots of less than 2 mm diameter are excluded, because these often cannot be distinguished empirically from soil organic matter or litter).

For a more thorough analysis, in addition to the carbon in above and below ground, we incorporate the following into our measurement: The carbon in litter, which is all the carbon

[34] According to the agricultural census of Brazil, the total cattle stock per pasture area in hectares equals approximately 0.30, whereas technical reports give 0.6 units per hectare in the UK and almost 1 in the US.

in all non-living biomass with a diameter less than the minimum diameter for dead wood (e.g. 10 cm), lying dead in various states of decomposition above the mineral or organic soil, as well as measures of carbon in mineral and organic soils (including peat) and measures of carbon in woody biomass not contained in the litter, either standing, lying on the ground, or in the soil.

Our calculation of the climate cost of deforestation is limited to its implied carbon emissions. We do not incorporate other types of greenhouse emissions, such as methane and oxides of nitrogen which may matter where forest fires play a significant role in forest degradation. We also highlight that the emissions coming from these other gases are typically an order of magnitude smaller than the ones associated with $CO_2$ (Federici et al., 2015).

# B Proofs

In this section, we provide the proofs for Propositions 1 - 4. We begin by characterizing a few key endogenous outcome in the steady state, which applies to all propositions, and then we take each proposition in turn.

## B.1 Characterizing the steady state

In the steady state, the stock of land is pinned down by setting $\dot{L}_i = 0$ in equation (10), which yields:

$$\delta_L L_i = Z_{i,T} N_{i,T}. \tag{B.1}$$

In turn, setting $\dot{q} = 0$ in equation 9 and using the pricing equation 8, we obtain the steady state rental rate of land:

$$r_i = \frac{(\rho + \delta_L)\, w_i}{Z_{i,T}}. \tag{B.2}$$

The last two equations imply imply the following relationship between payments to labor in the land-producing sector and payments to land:

$$r_i L_i = \frac{\rho + \delta_L}{\delta_L} w_i N_{i,T}. \tag{B.3}$$

In what follows, we also assume that $L_i < H_i$, that is, we assume the land frontier has room to expand in each country $i$.

## B.2 Proof of Proposition 1

Our definition of a small open economy (SOE) follows that of Alvarez and Lucas (2007). Specifically, country $i$ is considered a SOE in a limiting case where (i) $N_i, Z_{i,A}, Z_{i,M} \to 0$ and (ii) $Z_{i,M}^{\eta-1}/N_i \to \kappa_{i,M} > 0$, $Z_{i,A}^{\eta-1}/N_i \to \kappa_{i,A} > 0$.

Substituting this relation into market clearing for land, equation (11), we obtain

$$w_i N_{i,T} = \frac{\delta_L}{\rho + \delta_L} \sum_j \frac{1}{1 + t_{ij,A}} \left( \frac{w_i d_{ij,A} \left(1 + t_{ij,A}\right) / Z_{i,A}}{P_{j,A}} \right)^{1-\eta} X_{j,A}. \tag{B.4}$$

In turn, the market clearing for the manufacturing sector pins down the payments to labor there:

$$w_i N_{i,M} = \sum_j \frac{1}{1 + t_{ij,M}} \left( \frac{w_i d_{ij,M} \left(1 + t_{ij,M}\right) / Z_{i,M}}{P_{j,M}} \right)^{1-\eta} X_{j,M} \tag{B.5}$$

where in the above two equations, recall, $P_{j,s}$ and $X_{j,s}$ for $s \in \{A, M\}$ denote the CES price indices and industry-level expenditures in destination $j$.

First, let us show that the wage rate in the SOE, $w_i$, converges to a positive number. We guess that $w_i$ converges to a positive and finite constant, and then we will verify our guess. From our SOE assumption (i), it follows the the sectoral price indexes in each country and sector are independent of fundamentals in country $i$:

$$P_{j,s} \to \left( \sum_{i' \neq i} \left( w_{i'} d_{i'j,s} \left(1 + t_{i'j,s}\right) / Z_{i',s} \right)^{1-\eta} \right)^{\frac{1}{1-\eta}},$$

since $Z_{i,s} \to 0$.A similar argument shows that aggregate expenditure in each country and sector is independent of fundamentals in country $i$.

Next, noting that $N_{i,T} + N_{i,M} = N_i$, we can combine equations (B.4) and (B.5) and taking the limit defined by assumptions (i) and (ii), we verify that $w_i \in (0, \infty)$ :

$$w_i^{\eta} \to \sum_{j \neq i} \frac{\left(d_{ij,M} \left(1 + t_{i'j,M}\right)\right)^{1-\eta}}{P_{j,M}^{1-\eta}} \kappa_{i,M} X_{j,M} + \frac{\delta_L}{\rho + \delta_L} \sum_{j \neq i} \frac{\left(d_{ij,A} \left(1 + t_{i'j,A}\right)\right)^{1-\eta}}{P_{j,A}^{1-\eta}} \kappa_{i,A} X_{j,A},$$

since $X_{i,s} \to 0$, $\forall s$ and because each term of the right-hand side is a positive constant that does not depend on country $i$'s wage.

Having established that $w_i \in (0, \infty)$, we can now divide equation (B.4) by equation (B.5),

where the wages are canceled out to deliver:

$$N_{i,T} = N_{i,M} \frac{g_L}{\rho + g_L} \frac{d_{i,A}^{1-\eta}}{d_{i,M}^{1-\eta}} \frac{(1+t_{i,A})^{-\eta}}{(1+t_{i,M})^{-\eta}} \frac{\bar{X}_{-i,A}}{\bar{X}_{-i,M}}, \qquad \text{where} \qquad \bar{X}_{-i,s} \equiv \sum_{j \neq i} Z_{i,s}^{\eta-1} P_{j,s}^{\eta-1} X_{j,s};$$

Note that, here, for a clearer exposition, we let country $i$'s exports costs be common across all destinations, $d_{ij,s} = d_{i,s}$ and $t_{ij,s} = t_{i,s}$ for all $j \neq i$. Using the above expression, we obtain the effect of a uniform increase in country $i$'s export costs on the employment in the land-producing sector:

$$\frac{\mathrm{d} \ln N_{i,T}}{\mathrm{d} \ln d_{i,A}} = \frac{N_{i,M}}{N_i} (1-\eta); \tag{B.6}$$

Using equation (B.6) and the steady-state stock of land, $L_i = \frac{1}{g_L} Z_{i,T} N_{i,T}$, the impact on the stock of land can be similarly expressed as:

$$\frac{\mathrm{d} \ln L_i}{\mathrm{d} \ln d_{i,A}} = \frac{N_{i,M}}{N_i} (1-\eta). \tag{B.7}$$

Likewise, the responses of employment in the land-clearing sector and of cleared land to a change in tariffs are given by

$$\frac{d \ln N_{i,T}}{d \ln (1+t_{i,A})} = -\frac{N_{i,M}}{N_i} \eta$$

and

$$\frac{d \ln L_i}{d \ln (1+t_{i,A})} = -\frac{N_{i,M}}{N_i} \eta.$$

## B.3 Proofs of Propositions 2 and 3

We derive here an expression that we use as a starting point for both Propositions 2 and 3. Consider $I$ symmetric large open economies. Due to symmetry, we drop country subscripts.

We begin by noting that with symmetric economies, sectoral revenue equals sectoral expenditure country by country (because there is no motive for sectoral net exports). Next substituting the definition of sectoral expenditure shares (equation (4)), together with our assumptions on production technology, and with the equilibrium sectoral price indexes,

$$P_A = \frac{r}{Z_A} \left(\pi_A^D\right)^{\frac{1}{\eta-1}}, \qquad P_M = \frac{w}{Z_M} \left(\pi_M^D\right)^{\frac{1}{\eta-1}},$$

we obtain that land market clearing in each country is given by

$$rL = (1-h_A) \times b_A r^{1-\sigma} Z_A^{-(1-\sigma)} \left(\pi_A^D\right)^{-\frac{1-\sigma}{1-\eta}} E \tag{B.8}$$

while labor market clearing in manufacturing is given by

$$wN_M = (1 - h_M) \times b_M w^{1-\sigma} Z_M^{-(1-\sigma)} \left(\pi_M^D\right)^{-\frac{1-\sigma}{1-\eta}} E. \tag{B.9}$$

Here, $E$ denotes national expenditure, and $\pi_s^D$ is the "domestic expenditure share" in sector $s$, which is, under symmetry, equal to:

$$\pi_s^D = \frac{1}{(I-1)\left[d_s \times (1+t_s)\right]^{1-\eta} + 1} \tag{B.10}$$

Note that the trade barrier is inclusive of iceberg component, $d_s \geq 1$, and ad valorem equivalent import tariff, $(1 + t_s)$. Lastly, $(1 - h_s)$ denotes the fraction received by farmers from a dollar spent on varieties of sector $s$. Conversely, $h_s$ denotes the fraction collected by governments in the form of tariffs from a dollar spent on sector $s$,

$$h_s = \frac{t_s}{1+t_s}\left(1 - \pi_s^D\right) \tag{B.11}$$

We assume tariffs on non-agriculture to be zero, and so $h_M = 0$. Similarly, when agricultural tariffs are zero, $h_A = 0$ and the farmers receive the entirety of payments to agriculture. However, when agricultural tariffs are positive, a fraction $\frac{t_A}{1+t_A}$ of import payments is collected by governments of importing countries (which is then rebated to households), and the remaining fraction, $\frac{1}{1+t_A}$, is received by farmers in exporting countries. Equation B.11 follows by noting that (i) farmers receive all the domestic payments and (ii) imported share of expenditures equals $\left(1 - \pi_s^D\right)$.

Next, note that we can rewrite the labor resource constraint, using the steady state law of motion, equation B.1, as:

$$N_M = N - \frac{\delta}{Z_T} L. \tag{B.12}$$

Finally, divide equation B.8 by B.9, which yields

$$L = \left(\frac{1-h_A}{1-h_M}\right)\left(\frac{b_A}{b_M}\right)\left(\frac{Z_A}{Z_M}\right)^{\sigma-1}\left(\frac{\pi_A^D}{\pi_M^D}\right)^{\frac{1-\sigma}{\eta-1}}\left(\frac{r}{w}\right)^{-\sigma} \times N_M,$$

and substitute the rental rate of land using equation B.2 and $N_M$ from Equation B.12, to obtain:

$$L = \Phi \times \left(N - \frac{\delta}{Z_T} L\right), \qquad \Phi = \left(\frac{1-h_A}{1-h_M}\right)\left(\frac{b_A}{b_M}\right)\left(\frac{Z_A}{Z_M}\right)^{\sigma-1}\left(\frac{\pi_A^D}{\pi_M^D}\right)^{\frac{1-\sigma}{\eta-1}}\left(\frac{\rho+\delta}{Z_T}\right)^{-\sigma} \tag{B.13}$$

Equation B.13 is the basis for our derivations leading to Propositions 2 and 3.

### B.3.1 Proof of Proposition 2

Consider a worldwide uniform change in iceberg trade costs in agriculture, namely: $d_A \to d_A + \mathrm{d}d_A$. Based on Equation B.13, it is straightforward to show that[35]

$$\frac{\mathrm{d}\ln L}{\mathrm{d}\ln d_A} = \frac{N_M}{N}\frac{\mathrm{d}\ln \Phi}{\mathrm{d}\ln d_A}. \tag{B.14}$$

Supposing that tariffs are zero (and so $h_A = h_M = 0$), the only component in $\Phi$ that responds to a change in agricultural iceberg trade cost, $d_A$, is the domestic expenditure share in the agriculture sector, $\pi_A^D$, with the relationship governed by the following elasticity (derived from Equation B.10),

$$\frac{\partial \ln \pi_A^D}{\partial \ln d_A} = (\eta - 1)\left(1 - \pi_A^D\right). \tag{B.15}$$

Replacing B.15 when taking the derivatives of Equation B.13, we obtain:

$$\frac{\mathrm{d}\ln \Phi}{\mathrm{d}\ln d_A} = \frac{1-\sigma}{\eta - 1} \times \frac{\partial \ln \pi_A^D}{\partial \ln d_A} = (1-\sigma)\left(1 - \pi_A^D\right)$$

Replacing the above expression into Equation B.14 delivers the steady-state elasticity of the stock of land with respect to agricultural iceberg trace cost:

$$\frac{\mathrm{d}\ln L}{\mathrm{d}\ln d_A} = \frac{N_M}{N}(1-\sigma)\left(1 - \pi_A^D\right). \tag{B.16}$$

which reproduces Equation 14 in the main text.

### B.3.2 Borlaug's hypothesis

The original Borlaug's hypothesis considers agricultural productivity growth in a closed economy. Dropping the country subscript, note that $\pi_s^D = (1 - h_s) = 1$ in reference to Eq (B.13). Now, for an increase in agricultural productivity $Z_A$, the same steps as the ones which we took above, leads us to the following proposition.

**Proposition.** *(Borlaug's hypothesis) An agricultural productivity growth in a closed economy is land-saving when the elasticity of substitution between agriculture and non-agriculture is below one:*

$$\frac{\mathrm{d}\log L}{\mathrm{d}\log Z_A} = \frac{N_M}{N}(\sigma - 1) < 0 \quad \textit{for} \quad \sigma < 1.$$

[35] Taking the derivatives of Equation B.13 w.r.t. $d_A$, we obtain: $\frac{\mathrm{d}L}{\mathrm{d}d_A} = \frac{\mathrm{d}\Phi}{\mathrm{d}d_A} \times \left(N - \frac{\delta}{Z_T}L\right) - \Phi\frac{\delta}{Z_T}\frac{\mathrm{d}L}{\mathrm{d}d_A}$, which can be organized as: $\frac{\mathrm{d}L}{\mathrm{d}d_A} = \frac{\mathrm{d}\Phi}{\mathrm{d}d_A} \times \frac{N - \frac{\delta}{Z_T}L}{1 + \frac{\delta}{Z_T}\Phi}$. Considering that $\left(N - \frac{\delta}{Z_T}L\right) = N_M$ and $\left(1 + \frac{\delta}{Z_T}\Phi\right) = \Phi\frac{N}{L}$, the above can be expressed as: $\frac{\mathrm{d}\ln L}{\mathrm{d}\ln d_A} = \frac{\mathrm{d}\ln \Phi}{\mathrm{d}\ln d_A} \times \frac{N_M}{N}$

Note that another interpretation of Borlaug's hypothesis is the case of a uniform increase in agricultural productivities globally in all countries.

### B.3.3 Proof of Proposition 3

Now, consider a worldwide uniform change in ad valorem import tariffs in the agriculture sector, that is: $(1+t_A) \to (1+t_A) + \mathrm{d}(1+t_A)$. The same steps as in the derivations for the proof of Proposition 2 leads to the following expression:

$$\frac{\mathrm{d}\ln L}{\mathrm{d}\ln(1+t_A)} = \frac{N_M}{N}\left(\frac{1-\sigma}{\eta-1}\frac{\partial \ln \pi_A^D}{\partial \ln(1+t_A)} + \frac{\mathrm{d}\ln(1-h_A)}{\mathrm{d}\ln(1+t_A)}\right)$$

Similar to Equation B.15, $\frac{\partial \ln \pi_A^D}{\partial \ln(1+t_A)} = (\eta-1)\left(1-\pi_A^D\right)$. Consequently, we can rewrite the above equation as:

$$\frac{\mathrm{d}\ln L}{\mathrm{d}\ln(1+t_A)} = \frac{N_M}{N}(1-\sigma)\left(1-\pi_A^D\right) + \frac{N_M}{N}\frac{\mathrm{d}\ln(1-h_A)}{\mathrm{d}\ln(1+t_A)} \tag{B.17}$$

The above expression introduces the second term on the right-hand side, $\frac{\mathrm{d}\ln(1-h_A)}{\mathrm{d}\ln(1+t_A)}$, to the elasticity of land w.r.t. iceberg trade costs, Equation B.16. Recall that, in the presence of tariffs, farmers do not collect all the payments for agricultural consumption. Accordingly, the second term appears indicating that an increase in tariffs changes the pass-through to farmers. We can unpack this effect by taking the derivatives of Eq B.11, $(1-h_A) = 1 - \frac{t_A}{1+t_A}\left(1-\pi_A^D\right)$, w.r.t. to agricultural tariff, $t_A$,

$$\begin{aligned}\frac{\mathrm{d}\ln(1-h_A)}{\mathrm{d}\ln(1+t_A)} &= -\frac{1}{1-h_A}\frac{t_A}{1+t_A}\frac{\partial\left(1-\pi_A^D\right)}{\partial\ln(1+t_A)} - \frac{1-\pi_A^D}{1-h_A}\frac{\partial\left(\frac{t_A}{1+t_A}\right)}{\partial\ln(1+t_A)} \\ &= \underbrace{\frac{h_A}{1-h_A}(\eta-1)\pi_A^D}_{(+)\text{ if }\eta>1} + \underbrace{\frac{-1}{1-h_A}\frac{1-\pi_A^D}{1+t_A}}_{(-)}.\end{aligned} \tag{B.18}$$

Inspecting the two terms on the right-hand side of the above equation:

- *(a)* Holding fixed $\frac{t_A}{1+t_A}$, an increase in tariff shifts the demand for agriculture from foreign varieties to the domestic variety in each country, which raises the pass-through to farmers. This effect equals $\frac{h_A}{1-h_A}(\eta-1)\pi_A^D > 0$, which is positive under the empirically relevant case $\eta > 1$.
- *(b)* Holding fixed the imported expenditure share, $\left(1-\pi_A^D\right)$, an increase in tariff raises the fraction of payments received by farmers, which lowers the the pass-through to

farmers. Specifically, this negative effect equals $\left(-\frac{1-\pi_A^D}{1-h_A}\frac{1}{1+t_A}\right) < 0$.

Replacing for $\frac{\mathrm{d}\ln(1-h_A)}{\mathrm{d}\ln(1+t_A)}$ from Equation B.18 into B.17, we obtain:

$$\frac{\mathrm{d}\ln L}{\mathrm{d}\ln(1+t_A)} = \underbrace{\frac{N_M}{N}(1-\sigma)\left(1-\pi_A^D\right)}_{(+)\text{ if }\sigma<1} + \underbrace{\frac{N_M}{N}\frac{h_A}{1-h_A}(\eta-1)\pi_A^D}_{(+)\text{ if }\eta>1} + \underbrace{\frac{N_M}{N}\frac{-1}{1-h_A}\frac{1-\pi_A^D}{1+t_A}}_{(-)}, \quad \text{(B.19)}$$

which reproduces Equation 15 in the first part of Proposition 3.

Next, by replacing $h_A = \frac{t_A}{1+t_A}\left(1-\pi_A^D\right)$ into Equation B.19, we can express the elasticity of the stock of land w.r.t. agricultural tariff, compactly, as:

$$\frac{\mathrm{d}\ln L}{\mathrm{d}\ln(1+t_A)} = \frac{N_M}{N}\left(1-\pi_A^D\right)\left[\frac{t_A\pi_A^D}{1+t_A\pi_A^D}\eta-\sigma\right] \quad \text{(B.20)}$$

To inspect whether an increase in agricultural tariff $t_A$ raises the stock of land $L$, let us define the term in the brackets as a function of tariff rate $t_A$:

$$g(t_A) \equiv \frac{t_A\pi_A^D(t_A)}{1+t_A\pi_A^D(t_A)}\eta-\sigma, \qquad \text{where} \quad \pi_A^D(t_A) = \left[(I-1)\left(d_A(1+t_A)\right)^{1-\eta}+1\right]^{-1}$$

It is straightforward to check that: $g'(.) > 0$, $g(0) = -\sigma$, $h(\infty) = \eta - \sigma$. Provided that $\eta > \sigma > 0$, the Intermediate Value Theorem implies that $g(t_A) = 0$ has a unique solution $t_A^* > 0$ that satisfies:

$$t_A^*\pi_A(t_A^*) = \frac{\sigma}{\eta-\sigma}.$$

Moreover, it follows that $g(t_A)$ is negative when $t_A \in [0, t_A^*)$ and positive when $t_A \in (t_A^*, \infty)$. This observation, plus the fact that $\frac{N_M}{N}\left(1-\pi_A^D\right) > 0$ in Equation B.20, imply that $\frac{\mathrm{d}\ln L}{\mathrm{d}\ln(1+t_A)}$ is negative when $t_A \in [0, t_A^*)$, positive when $t_A \in (t_A^*, \infty)$, and zero when $t_A = t_A^*$. This completes the proof the Proposition 3.

## B.4 Proof of Proposition 4

Let us reiterate the assumptions of the proposition. Within each sector, goods are homogenous ($\eta \to \infty$) and preferences take a Cobb-Douglas form with $\beta_A = \beta$ and $\beta_M = 1-\beta$ denoting the fixed share of expenditure on agriculture and manufacturing respectively. The Cobb-Douglas form also implies $\sigma = 1$, which shuts down the structural change mechanism under Propositions 2 and 3. Countries only differ in their productivity to produce agriculture and manufacturing, $Z_{i,A}$ and $Z_{i,M}$. Note that, because we assume that $Z_{i,T} = Z_T$ is the same

across countries, the productivity of the land-producing sector is not a source of comparative or absolute advantage in agriculture. Likewise, because land $\delta_L$ is common across countries, reforestation capacity is not a source of comparative advantage either.

We proceed as follows. First we characterize the dynamic path and the steady state of an autarkic economy, with a focus on the allocation of labor across sectors and the corresponding stock of land and forest sustained in equilibrium. Second, we characterize equilibria for open economies, which will fully specialize either in manufacturing or in agriculture. Third, based on the previous results, we derive the statement in Proposition 4.

### B.4.1 Autarky

**Production.** Because of our focus on a single economy, in this subsection we drop the country index $i$; we also drop the index $t$ whenever it does not cause confusion. Take $p_A(t) = p_A$ as the numeraire at each time $t$.

Profit maximization in agricultural production yields a constant rental rate of land as a function of the agricultural price (i.e., the numeraire):

$$r = p_A Z_A,$$

noting that the agricultural sector always operates, whenever $L > 0$. Integrating forward the land asset pricing condition, Equation 9, we also obtain a constant price of land as a function of the numeraire

$$q_i = \frac{p_A Z_A}{\rho + \delta}.$$

Before studying the manufacturing and land-clearing sectors, note that with linear technologies it is not obvious ex-ante that both sectors will operate. We proceed with the assumption that they are, which will happen if the initial stock of land is low enough.

Profit maximization in the land-clearing sector yields the wage of workers in terms of the numeraire:

$$w_i = Z_{iT} \times \frac{p_A Z_A}{\rho + \delta},$$

i.e., the value of labor at the margin equates the PDV of returns of clearing $Z_{i,T}$ additional units of land.

**Demand.** Form our assumption on preferences, it follows that

$$x_M = \beta_M x^F$$
$$x_A = \beta_A x^F,$$

where $x^F$ is expenditure in final goods (agriculture and manufacturing) and $x_k$ is expenditure in sector $k$. Note that in autarky, $x^F = rL + wN_M$ (expenditure in final goods).

**Equilibrium.** Using labor market clearing in the manufacturing sector yields the allocation of labor as a function of relative factor rewards

$$N_M = \frac{1-\beta}{\beta}\frac{r}{w}L,$$

and after substituting equilibrium wages and rental rates into this expression, we obtain the allocation of labor as a function of the stocks of land and labor at each period

$$N_M = \frac{1-\beta}{\beta}\left(\frac{\rho+\delta}{Z_T}\right)L$$
$$N_T = N - N_M$$

Note that higher stocks of land $L$ lead to more labor in manufacturing, as it scales demand for both goods up.

Finally using $N_T$ in the law of motion of land, Equation 10, we obtain the following differential equation for land accumulation

$$\dot{L} = Z_T N - KL,$$

with

$$K \equiv \frac{1-\beta}{\beta}(\rho+\delta) + \delta.$$

Because $K > 0$, the solution to this equation is stable, and given by

$$L(t) = L_{ss} + [L(0) - L_{ss}]\, e^{-Kt},$$

with $L_{ss} = Z_T N/K$ denoting the steady-state stock of land.

Note also that the ratio of prices that clears markets at each point is:[36]

$$\frac{p_A}{p_M} = \frac{1}{(w/Z_M)} = \frac{Z_M}{Z_T Z_A}(\rho + \delta).$$

Variation in this autarky price ratio across countries is determined entirely by the ratio of productivities in agriculture and manfacturing, $Z_{i,A}$ and $Z_{i,M}$, since the other terms are constant by assumption.

**Steady state** In the steady state, $\dot{L} = 0$, so

$$L = \frac{Z_T N}{K}$$

and all prices are constant (as they are outside of the steady state).

Using the equilibrium allocations of labor across manufacturing and land-clearing, and substituting the equilibrium land stock we obtain:

$$\frac{N_M}{N_T} = \frac{1-\beta}{\beta}\left[\frac{\rho+\delta}{\delta}\right] \tag{B.21}$$

This equation is important because it is the basis of the comparison of open and closed economies that allows us to establish the results in Proposition 4. Note the similarity with the standard Cobb-Douglas (that labor is allocated in accordance to expenditure shares), only the term in square brackets adjusts for the fact that a unit of labor in tree-cutting labor delivers a flow of agricultural goods.

[36] If the land-clearing sector is not open, then market clearing yields the following ratio of prices, which varies over time, as the stock of land changes.

$$\frac{p_M}{p_A} = \frac{1-\beta}{\beta}\frac{Z_A}{Z_M}\frac{L}{N}.$$

This is the case when $q < w/Z_M$, that is, when

$$\frac{L}{N} > \frac{1-\beta}{\beta}\frac{Z_T}{\rho+\delta}$$

so land is too abundant relative to demand of agricultural goods. If this initial condition is met, the law of motion of land boils down to

$$\dot{L} = -\delta.$$

Along the transition path, the relative price of manufacturing decreases, as agricultural production becomes more scarce, up to the point that land-clearing becomes profitable and the system evolves as described in the main body of the proof.

### B.4.2 International Trade – Specialization in Manufacturing

Now consider what happens when the economy opens up to a free trading system. Suppose country $i$ starts with a stock of land given by $L_i(0) = L_{i,ss}$. Denote world prices by a star, so the price of agriculture is given by $p_A^*$.

**Production.** Country $i$ will specialize in manufacturing when $p_A^*/p_M^* < p_{i,A}/p_{i,M}$. Because the economy specializes in manufacturing, we still have that profit maximization in that sector will pin down wages:

$$w_i = p_{i,M}^* Z_{i,M}.$$

At the same time, given the international prices, country $i$ will not operate the land-clearing sector and there will be no entry into landowning.[37] Labor entirely specializes in manufacturing

$$Q_{iM} = Z_{i,M} N_i$$

and the law of motion of land in the transition to steady state is

$$\dot{L} = -\delta L.$$

Note, however, that during the transition $L > 0$, so land markets must clear, and $r_i = p_A^* Z_{i,A}$.

**Demand.** International trade decouples production and consumption. Total expenditure in final goods is given by

$$x_i^F = w_i N_i + r_i L$$

at each point in time. Expenditure in final goods reflects the Cobb-Douglas shares $\beta$ and $1-\beta$. Importantly, as the stock of land decreases, total expenditure in final goods in the economy decreases as well.

**Steady state.** In the steady state, the allocation of labor is still $N_{i,M} = N$, while no land is sustained in equilibrium, $L_i = 0$. Total expenditure is then $x_i^F = w_i N_i$.

[37] To see why, suppose the land-clearing sector is opperational. Profit maximization implies $w_i = Z_{iT} q_i$, which implies the following relation between international prices and domestic productivities: $p_A^*/p_M^* = Z_{i,M}(\rho + \delta)/(Z_{i,A} Z_T)$. The right hand side of this expression, however, is the autarky relative price of country $i$. This contradicts the premise that $p_A^*/p_M^* < p_{i,A}/p_{i,M}$.

### B.4.3 International Trade – Specialization in Agriculture.

**Production.** Country $i$ will specialize in manufacturing when $p_A^*/p_M^* > p_{i,A}/p_{i,M}$. As before, given international prices, one can show that the manufacturing sector shuts down immediately, which means that all labor moves to land-clearing

$$N_{i,T} = N$$

and the law of motion of land at each time is given by

$$\dot{L}_{i,T} = Z_{i,T} N_i - \delta L_i.$$

Because the agricultural sector is operational, we must still have free-entry into land holding, as well as profit maximization in land-clearing and in agricultural production, which yields the following equilibrium prices

$$\begin{aligned} r_i &= p_A^* Z_{iA} \\ q_i &= \frac{p_A^* Z_{iA}}{r + \delta} \\ w_i &= \frac{Z_{iT} p_A^* Z_{iA}}{r + \delta} \end{aligned}$$

**Demand.** As before, international trade decouples production and consumption. Total expenditure in final goods now is given by

$$x_i^F = w_i N + r_i L_i,$$

which grows towards the new steady state.

**Steady state.** We impose $\dot{L} = 0$, which yields equilibrium land stocks:

$$L_i = \frac{Z_T}{\delta_L} N_i$$

(independent of preferences) and the steady state production of agriculture is

$$Q_{iA} = \frac{Z_{iA} Z_T}{\delta_L} N.$$

## B.5 Proposition 4

We focus now on the steady state of the trading economy. Recall that, without loss of generality, we order countries such that $Z_{i,A}/Z_{i,M}$, decreases in $i \in [0,1]$, which, as we established above, translates into a ranking of autarky prices.

In the free trade equilibrium, the assumption that goods are homogeneous in each sector implies there is a single relative price of manufacturing relative to agriculture. We denote this price by $p^* = p_M^*/p_A^*$. Let country $i^*$ be the the marginal country whose autarky price coincides with the free-trade price:

$$p^* = \frac{Z_{i^*,A} Z_T}{(\rho + \delta_L) Z_{i^*,M}} \tag{B.22}$$

All countries whose autarky relative price of manufacturing is higher than $p^*$ completely specialize in agriculture, while the rest completely specialize in manufacturing.The marginal country $i = i^*$ may produce both goods, but has measure zero.

Next, note that with Cobb-Douglas preferences, the global expenditure share on agriculture is $\beta$, while that on manufacturing is $1-\beta$. Therefore, market clearing requires:

$$\frac{p_M^*}{p_A^*} = \frac{\beta_M}{\beta_A} \frac{\int_0^{i^*} \frac{Z_{i,A} Z_T}{\delta} N_i di}{\int_{i^*}^1 Z_{i,M} N_i di} \tag{B.23}$$

since global production of each good is given by $Q_M^W = \int_{i^*}^1 Z_{i,M} N_i di$ and $Q_A^W = \int_0^{i^*} \delta_L^{-1} Z_{i,A} Z_T N_i di$, since in each country specialized in agriculture $Q_{i,A} = Z_{i,A} Z_T N_i / \delta_L$.

An equilibrium consists of a cutoff country $i^*$ and an equilibrium relative price of agriculture $p^*$, such that equations B.22 and B.23 jointly hold. The right-hand side of equation B.22 is decreasing in $i^*$ by our choice of ordering. The right-hand side of equation B.23 is strictly increasing, and moreover, equals zero at $i^* = 0$ and tends to infinity as $i^* \to 1$. This means the equilibrium exists and is unique. This proves result (i) in Proposition 4.

To determine the total demand for factors under free trade, we rearrange equation B.23 as

$$\frac{1-n}{n} = \frac{\rho + \delta}{\delta} \frac{1-\beta}{\beta} \frac{\mathbb{E}\left[Z_{i,A} | i \leq i\right] / Z_{i^* A}}{\mathbb{E}\left[Z_{i,M} | i > i\right] / Z_{i^* M}} \tag{B.24}$$

where $n \equiv \int_0^{i^*} N(i)\, di / \int_0^1 N_i(i)\, di$ is the share of countries specialized in agriculture and, since all countries have the same size, it is also the global share of labor in agriculture.

Recalling the allocation of labor in autarky, given in Equation B.21, we see that trade decreases the global amount of labor in agriculture relative to autarky if $n < \beta$, i.e., if the second term on the right-hand side of B.24 is greater than one.

We now obtain sufficient conditions such that the second term on the right hand side of B.24 is greater or smaller than one. When there is positive selection into sector $g \in \{A, M\}$, the average country specializing in that sector is more productive than the marginal country, i.e.,

$$\mathbb{E}\left[Z_{i,g} | i \geq i^*\right] / Z_{i^*,g} > 1,$$

while the opposite is true with negative selection.

We distinguish two cases to obtain result (ii) in Proposition 4.

- First, suppose $Z_{i,M}$ is decreasing in $i$. Given that by our ordering of countries, $Z_{i,A}/Z_{i,M}$ is decreasing in $i \in [0,1]$, this implies that $Z_{i,A}$ must be also decreasing in $i$.—*i.e.,* comparative and absolute advantage are aligned in agriculture but reversely aligned in manufacturing. This ensures positive selection into agriculture and negative selection into manufacturing, so the right-hand side of B.24 is greater than one. That is, $\mathbb{E}\left[Z_{i,A} | i \leq i^*\right] > Z_{i^*,A}$ and $\mathbb{E}\left[Z_{i,M} | i > i^*\right] < Z_{i^*,M}$. Under this case, global land use decreases, or equivalently, global forest area expands.

- Second, suppose that $Z_{i,A}$ is increasing in $i$. Given our ordering of countries, this implies that $Z_{i,M}$ must increase in $i$ as well. This ensures that there is negative selection into agriculture and positive selection into manufacturing, so the right-hand side of B.24 is smaller than one.

# C The Quantitative model

This section introduces in detail the model we use for quantification.

## C.1 Time, Geography and Markets

The economy operates in continuous time $t \in [0, \infty)$, and divided into multiple countries, indexed by $i, j = 1, ..., N$. Each country $i$ is endowed by a fixed, time-invariant amount of land, $H_i$, and an exogenous path of labor force, $N_i(t)$. Each country's land consists of agricultural land, $L_i(t)$, and forest area, $F_i(t)$, such that $H_i = L_i(t) + F_i(t)$, with the agricultural land itself being divided into *usable* land $U_i(t)$ and *fallow* land $O_i(t)$, such that $L_i(t) = U_i(t) + O_i(t)$.

There is a land-clearing sector, labelled as $T$, that converts forest and fallow land into new land to be used in the production of consumption goods $g \in \mathcal{G}$. These consumption goods span multiple industries, consisting of agricultural goods $(1, ..., K)$, manufacturing $(M)$, and

services ($S$),

$$\mathcal{G} \equiv \left\{ \underbrace{1, ..., K}_{\text{Agriculture}} \quad , \quad \underbrace{M}_{\text{Manufacturing}} \quad , \underbrace{S}_{\text{Service}} \right\},$$

with each industry $g \in \mathcal{G}$ to be further differentiated into varieties by country of origin. For each variety of industry $g$ originated from supplying country $i$, there is a market in country $j$—corresponding to the international market for origin $i-$destination $j-$industry $g$. Shipping $g$ from $i$ to $j$ entails trade costs $\tau_{ij,g} = (1 + t_{ij,g})\, d_{ij,g}$ where $t_{ij,g}$ denotes the ad valorem import tariff rate charged by importing country $j$, and $d_{ij,g} \geq 1$ represents the iceberg trade cost, with $t_{ii,g} = 0$ and $d_{ii,g} = 1$.

Markets are perfectly competitive. We drop the time index whenever it does not create confusion. Hereafter, we let $\dot{y} = dy/dt$ for any variable $y$.

## C.2 Households

### C.2.1 Preferences

Each country has a representative household with a three-tier demand system. The upper tier aggregates the composites of agriculture ($A$), manufacturing ($M$), and services ($S$) into final consumption using a substitution elasticity $\sigma$:

$$C_i = \left[ \sum_{s \in \{A,M,S\}} b_{i,s} C_{i,s}^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}},$$

where $C_{i,s}$ represents the consumption of each sector. The middle tier defines $C_{i,s}$ for each sector. For agriculture ($s = A$), the agricultural composite combines disaggregated agricultural industries with a substitution elasticity $\kappa$:

$$C_{i,A} = \left[ \sum_{k=1}^{K} b_{i,k} C_{i,k}^{\frac{\kappa-1}{\kappa}} \right]^{\frac{\kappa}{\kappa-1}}.$$

For manufacturing ($s = M$) and services ($s = S$), the composites are simply $C_{i,M}$ and $C_{i,S}$, respectively. The lower tier aggregates national varieties of each industry $g \in \mathcal{G}$ with a substitution elasticity $\eta_g$:

$$C_{i,g} = \left[ \sum_{j=1}^{N} b_{ij,g} C_{ij,g}^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta}{\eta-1}}, \qquad g \in \mathcal{G}.$$

### C.2.2 Costs, Prices, and Expenditure Shares.

Cost minimization implies that the marginal cost of producing good $g$ in country $i$ is given by:

$$c_{i,g} = \frac{1}{Z_{i,g}} \left( w_{i,g}^{\gamma_{i,g}} r_i^{1-\gamma_{i,g}} \right)^{\alpha_{i,g}} \left( P_{i,g}^I \right)^{1-\alpha_{i,g}}, \tag{C.25}$$

where $w_{i,g}$ is the wage rate in country $i-$industry $g$, $r_i$ is the rental rate of land, and $P_{i,g}^I$ is the price of the composite intermediate input.

Country $j$'s expenditure in good $g$ produced by country $i$ equals

$$\pi_{ij,g} = \frac{b_{ij,g} \left( c_{i,g} \tau_{ij,g} \right)^{1-\eta_g}}{p_{j,g}^{1-\eta_g}}, \tag{C.26}$$

where $c_{i,g}$ is the marginal cost of production, and $p_{j,g}$ is the price index of good $g$ in destination market $j$, given by:

$$p_{j,g} = \left[ \sum_{i=1}^{N} b_{ij,g} \left( c_{i,g} \tau_{ij,g} \right)^{1-\eta_g} \right]^{\frac{1}{1-\eta_g}}, \qquad g \in \mathcal{G} \equiv \{1, ..., K, M, S\}. \tag{C.27}$$

Note again that the trade shares, $\pi_{ij,g}$, and price indexes, $p_{j,g}$, are common to both consumers and intermediate input users in country $i$ good $g$. Within-agriculture consumption expenditure shares equal:

$$\beta_{i,k} = b_{i,k} \left( \frac{p_{i,k}}{P_{i,A}} \right)^{1-\kappa}, \qquad k \in \{1, ..., K\} \tag{C.28}$$

The sector-level price index of agriculture, $P_{i,A}$, follows from the CES specification between agricultural goods, and those of manufacturing and service are trivially given by their corresponding good-level price indices:

$$P_{i,A} = \left[ \sum_{k=1}^{K} b_{i,k} p_{i,k}^{1-\kappa} \right]^{\frac{1}{1-\kappa}}, \qquad P_{i,M} = p_{i,M}, \qquad P_{i,S} = p_{i,S} \tag{C.29}$$

Lastly, the expenditure share on sector $s \in \{A, M, S\}$ equals:

$$\beta_{i,s} = b_{i,s} \left( \frac{P_{i,s}}{P_i} \right)^{1-\sigma}, \tag{C.30}$$

where the final consumer price is given by,

$$P_i = \left[ \sum_{s \in \{A,M,S\}} b_{i,s} P_{i,s}^{1-\sigma} \right]^{\frac{1}{1-\sigma}}. \tag{C.31}$$

For manufacturing and services $g = s \in \{M, S\}$, $\beta_{i,g}^F = \beta_{i,s}$; for agricultural products $g \in (k = 1, ..., K \mid A)$, $\beta_{i,g}^F = \beta_{i,A}\beta_{i,k}$.

### C.2.3 Worker Mobility and Sectoral Choices

Workers are forward looking and have perfect foresight. They are endowed with one unit of labor, which they supply inelastically. Workers receive opportunities to move out of their current sector with an arrival rate of $\psi$. When an opportunity arrives, a worker draws a vector of preference shocks $\varepsilon_{i,s}^N$ from a Type-I extreme value distribution with dispersion parameter $\nu$, and can choose to reallocate from its current sector $s$ to another sector $s'$, subject to moving cost $f_{i,ss'}^N$.

Supposing perfect labor mobility within the agriculture sector, agricultural industries pay the same wage $w_{i,A} = w_{i,1} = ... = w_{i,K}$. However, wage rates are different only between broadly-defined sectors of agriculture ($A$), manufacturing ($M$), services ($S$) and the land-clearing sector ($T$). Given these assumptions, the expected present value of the stream of a worker's utility who is currently in sector $s$, $v_{i,s}^N$ , is the solution to:

$$(\rho + \psi)\, v_{i,s}^N = u\left(\frac{w_{i,s}}{P_i}\right) + \psi W_{i,s} + \dot{v}_{i,s}^N, \tag{C.32}$$

where $W_{i,s}$ is the expected continuation value for a worker employed in sector $s$ who receives a moving opportunity,

$$W_{i,s} \equiv \mathbb{E}\left[\max_{s'} \left\{ v_{i,s'}^N - f_{i,ss'}^N + \varepsilon_{i,s'}^N \right\}\right] = \nu \log \sum_{s' \in S} \exp\left(\frac{1}{\nu}\left(v_{i,s'}^N - f_{i,ss'}^N\right)\right). \tag{C.33}$$

Conditional on the arrival of the option to move, the probability of moving from sector $s$ to $s'$ equals:

$$\mu_{i,ss'} = \frac{\exp\left(\left(v_{i,s'}^N - f_{i,ss'}^N\right)/\nu\right)}{\sum_{l \in S} \exp\left(\left(v_{i,l}^N - f_{i,sl}^N\right)/\nu\right)}. \tag{C.34}$$

## C.3 Final and Intermediate Good Production

### C.3.1 Technology

Production technologies in country $i$, industry $g$ takes a Cobb-Douglas form:

$$Q_{i,g} = Z_{i,g}\left(N_{i,g}^{\gamma_{i,g}} L_{i,g}^{1-\gamma_{i,g}}\right)^{\alpha_{i,g}} \left(Q_{i,g}^{I}\right)^{1-\alpha_{i,g}}, \qquad g \in \mathcal{G};$$

where $Z_{i,g}$ is total factor productivity, $N_{i,g}$, $L_{i,g}$, and $Q_{i,g}^{I}$ are, respectively, the use of labor, land, and intermediate inputs in industry $g$, and $\alpha_{i,g}$ is the value added share divided between land and labor with shares $\gamma_{i,g}$ and $(1-\gamma_{i,g})$. The intermediate input $Q_{i,g}^{I}$ is an aggregate over all industries, which retains the same three-tier CES structure as preferences:

$$Q_{i,g}^{I} = \left[\sum_{s\in\{A,M,S\}} b_{i,sg}^{I} M_{i,sg}^{\frac{\sigma^{I}-1}{\sigma^{I}}}\right]^{\frac{\sigma^{I}}{\sigma^{I}-1}}$$

$$M_{i,Ag} = \left[\sum_{k=1}^{K} b_{i,kg}^{I} M_{i,kg}^{\frac{\kappa^{I}-1}{\kappa^{I}}}\right]^{\frac{\kappa^{I}}{\kappa^{I}-1}}.$$

$$M_{i,g'g} = \left[\sum_{j=1}^{N} b_{ij,g} M_{ij,g'g}^{\frac{\eta^{I}-1}{\eta^{I}}}\right]^{\frac{\eta^{I}}{\eta^{I}-1}}, \qquad g \in \mathcal{G},$$

note that in the lowest tier, the shifters are shared with those of consumers.

### C.3.2 Expenditure shares

Given our assumptions, the unit costs faced by producers in country $i$ utilizing good $g \in \mathcal{G}$ as an intermediate input, $c_{i,g}$, coincide with those faced by final good consumers (equation (C.25)). So do the expenditure shares across sources within sector $g$, $\pi_{ij,g}$ (equation , (C.26)) and goods prices, $p_{i,g}$ (equation (C.27)).

In turn, the CES input aggregators imly that intermediate input expenditure shares within agriculture equal

$$\beta_{i,kg}^{I} = b_{i,kg}^{I}\left(\frac{p_{i,k}}{P_{i,Ag}^{I}}\right) \qquad k \in \{1,...,K\},$$

where

$$P^I_{i,Ag} = \left[\sum_{k=1}^{K} b^I_{i,kg} p^{1-\kappa}_{i,k}\right]^{\frac{1}{1-\kappa}}, \qquad P^I_{i,Mg} = p^I_{i,Mg}, \qquad P^I_{i,Sg} = p^I_{i,Sg} \forall g \in \mathcal{G}. \tag{C.35}$$

Thus for manufacturing and services $g = s \in \{M, S\}$, $\beta^F_{i,g} = \beta_{i,s}$; for agricultural products $g \in (k = 1, ..., K \mid A)$, $\beta^F_{i,g} = \beta_{i,A}\beta_{i,k}$.

## C.4 Land-Clearing and Landowners.

Land shares. Let $z_i$ denote the share of agricultural land in total country area, $z_i$, and $u_i$ represent the share of currently usable agricultural land:

$$z_i \equiv L_i/H_i, \qquad u_i \equiv U_i/L_i$$

Accordingly, the share of forest in total country area is given by $F_i/H_i = (1 - z_i)$, and the share of fallow land in total country area equals $O_i/H_i = z_i \times (1 - u_i)$.

**Land-clearing sector.** There are symmetric land-producing firms seek to produce usable land by converting (1) forest or (2) fallow land. Production in each of these two sub-sectors requires the employment of labor under decreasing-returns-to-scale technologies. Labor is freely mobile between the two sub-sectors, and so, the marginal product of labor must equalize between them. Moreover, we assume that the flows of land-conversion from forest or fallow land provide homogeneous land, and so, at any point in time, there is a single market price $q_i$ for new land regardless of its source.

The productivity in the land-clearing sector depends on the available stock of forest and fallow land. Usable land is generated by converting forest ($F$) and fallow land ($O$), which serve as specific factors, and employing labor as a variable input. The corresponding production technologies are expressed as:

$$Q^{FU}_{i,T} = \underbrace{\zeta_{i,F}\left(1 - z_i\right)^{\lambda_F}}_{J_i(z_i)} \left(N^{FU}_{i,T}\right)^{\gamma_F}, \qquad Q^{OU}_{i,T} = \underbrace{\zeta_{i,O}\left(z_i\left(1 - u_i\right)\right)^{\lambda_O}}_{H_i(z_i(1-u_i))} \left(N^{OU}_{i,T}\right)^{\gamma_O};$$

with total production and employment of the land-clearing sector given by:

$$Q_{i,T} = Q^{FU}_{i,T} + Q^{OU}_{i,T}$$

$$N_{i,T} = N^{FU}_{i,T} + N^{OU}_{i,T}. \tag{C.36}$$

In our specification, $J_i(.)$ and $H_i(.)$ represent the productivity of converting forest and fallow land into usable land, and $\{\gamma_F, \gamma_O\}$ denote the output elasticities with respect to labor —which are bounded between zero and one. Furthermore, $\{\zeta_{i,F}, \zeta_{i,O}\}$ are exogenous parameters, and $\{\lambda_F, \lambda_O\}$ are the elasticities of productivity $J_i(.)$ and $H_i(.)$ with respect to the available stock of forest and fallow land. The representative land-clearing producer treats these productivities as fixed and does not internalize the effects of its production decisions on them.

Since labor is freely mobile within the land-producing sector, the marginal product of labor equalizes between the two sub-sectors, which in turn pins down the wage rate $w_{i,T}$

$$w_{i,T} = \gamma_O \zeta_{i,O} \times \left(z_i \left(1 - u_i\right)\right)^{\lambda_O} \times \left(N_{i,T}^{OU}\right)^{\gamma_O - 1} \tag{C.37}$$

$$w_{i,T} = \gamma_F \zeta_{i,F} \times \left(1 - z_i\right)^{\lambda_F} \times \left(N_{i,T}^{FU}\right)^{\gamma_F - 1} \tag{C.38}$$

Moreover, since the two sub-sectors produce a homogenous usable land, they face the same price level $q_i$. Cost minimization implies that:

$$q_i = \frac{w_{i,T}}{\gamma_O \zeta_{i,O} \times \left(z_i \left(1 - u_i\right)\right)^{\lambda_O}} \left(N_{i,T}^{OU}\right)^{1-\gamma_O} \tag{C.39}$$

$$q_i = \frac{w_{i,T}}{\gamma_F \zeta_{i,F} \times \left(1 - z_i\right)^{\lambda_F}} \left(N_{i,T}^{FU}\right)^{1-\gamma_F} \tag{C.40}$$

**Free entry condition and value function of landowners.** There is a continuum of landowners who are risk-neutral and have perfect foresight. Each of them owns one unit of usable land which can be rented out at a rate $r_i$. Landowners discount the future at a rate of $\rho$ and, with arrival rates of $\delta_F$ and $\delta_O$, each unit of usable land "depreciates", turning into forest and fallow land respectively. Let $v_{i,F}$ and $v_{i,O}$ denote the per-unit discounted present value of usable land when converted, respectively, from forest and fallow land. The no-arbitrage condition requires the return to land-conversion to be equal between the two sub-sectors, $v_{i,F} = v_{i,O} = v_i$, and the free entry condition requires:

$$v_i = q_i. \tag{C.41}$$

Similar to the Stylized Model in Section 4, the value function is given by:

$$\rho v_i = r_i + \dot{v}_i - (\delta_O + \delta_F) \tag{C.42}$$

where $r_i$ is (as before) the rental rate of usable land, and (new to this extension) $\delta_O$ and $\delta_F$ are respectively the regrowth rates of fallow land and forest.

## C.5 Sales, Expenditures and Market Clearing Conditions.

Country $i'$s total sales in industry $g$ equal:

$$Y_{i,g} = \sum_j \frac{\pi_{ij,g}}{1+t_{ij,g}} X_{j,g}, \qquad g \in \mathcal{G} \tag{C.43}$$

The expenditure, $X_{j,g},$, is comprised of final and intermediate demand:

$$X_{i,g} = \underbrace{\beta^F_{i,g} E_i}_{\text{final expenditure}} + \underbrace{\sum_{g' \in G} \beta^I_{i,g'g} \left(1-\alpha_{i,g'}\right) Y_{i,g'}}_{\text{intermediate expenditure}}. \tag{C.44}$$

Here, $\beta^F_{i,g}$ is the final expenditure share on each good $g$. Labor market clearing requires the wage bill to equal payments to labor in each sector $s$, that is:

$$w_{i,A} N_{i,A} = \sum_{k=1}^{K} \alpha_{i,k} \gamma_{i,k} Y_{i,k}, \quad w_{i,M} N_{i,M} = \alpha_{i,M} \gamma_{i,M} Y_{i,M}, \quad w_{i,S} N_{i,S} = \alpha_{i,S} \gamma_{i,S} Y_{i,S} \tag{C.45}$$

Land market clearing requires total land rents to equal payments to land:

$$r_i U_i = \sum_{g \in \mathcal{G}} \alpha_{i,g} \left(1-\gamma_{i,g}\right) Y_{i,g} \tag{C.46}$$

The profits in the land-producing sector are given by: $\Pi_{i,T} = \left(1-\gamma_{i,T}\right) q_i Q_{i,T}$. In turn, the market clearing in the production of new land entails $Q_{i,T} = x_i$ in every country $i$.

Lastly, under balance of trade, final expenditure equals the sum of factor rewards,[38]

$$E_i = r_i U_i + \sum_{s=\{A,M,S\}} w_{i,s} N_{i,s} + T_i, \tag{C.47}$$

where $T_i$ is the country $i$'s revenue from tariffs, which the government rebates to the consumers as a lump sum:

$$T_i = \sum_{g \in \mathcal{G}} \sum_j \frac{t_{ji,g}}{1+t_{ji,g}} \pi_{ji,g} X_{i,g}$$

[38]Since the net payment to land is $(r_i U_i - w_{i,T} N_{i,T})$, the balance of budget could be equivalently expressed as $E_i = (r_i U - w_{i,T} N_{i,T}) + \sum_{s=\{A,M,S,T\}} w_{i,s} N_{i,s}$. Moreover, market clearing conditions ensure that final expenditure also equals aggregate value added, $E_i = \Sigma_g \alpha_{i,g} Y_{i,g}$.

## C.6 Law of Motion for Labor and Land.

To keep track of worker reallocation across sectors, we define the matrix, $\mathbf{M}_i$, with elements $\mathbf{M}_i[s,s'] = \psi\mu_{i,ss'}$ if $s \neq s'$, and $\mathbf{M}_i[s,s'] = -\psi(1-\mu_{i,ss})$ if $s = s'$.[39] In country $i$, the mass of workers in each sector evolves according to:

$$\dot{\mathbf{N}}_i = \mathbf{M}_i^T \mathbf{N}_i, \tag{C.48}$$

where $\mathbf{N}_i$ is the vector of employments across sectors in country $i$. The above equation together with the initial labor allocation, $\mathbf{N}_i(0)$, characterize the evolution of labor.

The evolution of land follows from the definition of the share of agricultural land in total country area, $z_i \equiv L_i/H_i$, and the share of usable land within the agricultural land, $u_i \equiv U_i/L_i$. Accordingly, the fallow land evolves according to:

$$\dot{O}_i = -Q_{i,T}^{OU} - \delta_F \overbrace{(1-u_i)z_iH}^{O_i} + \delta_O \overbrace{u_i z_i H_i}^{U_i}, \tag{C.49}$$

where $(Q_{i,T}^{OU})$ is the out-flow from fallow land to usable land, $\delta_F O_i$ is the outflow from fallow land to forest, and $(\delta_O U_i)$ is the in-flow from the usable land to fallow land. Similarly, the forest area evolves according to:

$$\dot{F}_i = -Q_{i,T}^{FU} + \delta_F z_i H_i \tag{C.50}$$

where $\delta_F z_i H_i$ is the inflow to forest from usable and fallow land. The above two equations, in turn, pin down the law of motion for usable land:

$$\dot{U} = Q_{i,T}^{FU} + Q_{i,T}^{OU} - (\delta_O + \delta_F) u_i z_i H_i \tag{C.51}$$

Here, in contrast to the Stylized Model of Section 4, generically $\dot{U}_i \neq -\dot{F}$. Under this extension, therefore, the expansion of agricultural land use can be different from the loss of forest area. For our quantitative analysis, this is an important consideration because our empirical findings suggest that in response to demand shocks the agricultural land use may expand at a different rate than the rate of deforestation.

Coupled with initial stocks of productive land and forests, $L_i(0)$ and $F_i(0)$, Deforestation is the decrease in forest cover, $\dot{D}_i \equiv -\dot{F}_i$.

[39] When population growth is nonzero, we alter the on-diagonal elements to $\mathbf{M}_i[s,s'] = -\psi(1-\mu_{i,ss}) + \delta_i^N$, where $\delta_i^N$ is country $i$'s population growth at a point in time. This is equivalent to assuming that workers who enter the workforce do so in each sector with equal probability.

## C.7 Equilibrium

We break down the definition of equilibrium into two parts: a static and a dynamic equilibrium. Let $\mathbf{Z}(t) \equiv \{Z_{i,g}(t)\}_{i,g}$, $\mathbf{B} \equiv \left\{\{b_{ij,g}\}_{i,j,g}, \{b_{i,k}\}_{i,k}, \{b_{i,s}\}_{i,s}, \left\{b^I_{i,k}\right\}_{i,k}, \left\{b^I_{i,s}\right\}_{i,s}\right\}, \Upsilon \equiv \left\{\sigma, \kappa, \{\eta_g\}, \sigma^I, \kappa^I, \left\{\eta^I_g\right\}\right\}$, $\mathbf{T}(t) = \{d_{ij,g}(t)\}_{ij,g}$

**Static Equilibrium.** At any time $t$, given (i) technologies, iceberg trade costs and tariffs, and preferences, $\mathbf{Z}_t, \mathbf{T}_t, \mathbf{B}, \Upsilon$ (ii) labor allocations across sectors $\{N_{i,s}(t)\}_{i,s}$ and land stocks $\{U_i(t), O_i(t), F_i(t)\}_i$, and (iii) the price of new land $\{q_i(t)\}_i$, a static equilibrium consists of (i) factor rewards $\{w_{i,s}(t)\}_{i,s}$ and $\{r_i(t)\}_i$, (ii) labor allocations across land-clearing technologies $\left\{N^{FU}_{i,T}(t), N^{OU}_{i,T}(t)\right\}_i$, such that land markets clear (equation (C.46)), labor markets clear in each sector (equations (C.45) and (C.36)), and new land is priced at marginal cost (equation (C.39)).

**Dynamic Equilibrium.** Given (i) exogenous paths of technologies, iceberg trade costs and tariffs, and preferences, $[\mathbf{Z}(t), \mathbf{T}(t)]_t, \mathbf{B}, \Upsilon$, (ii) exogenous paths of labor supplies $[\{N_i(t)\}_i]$, (iii) initial land stocks, $\{U_i(0), O_i(0), F_i(0)\}_i$, a dynamic equilibrium consists of (i) paths of land prices and for the stocks of land $[\{q_i(t), U_i(t), O_i(t), F_i(t)\}_i]$ and (ii) paths of labor allocations across sectors $\left[\{N_{i,s}(t)\}_{i,s}\right]$, such that the paths of labor supplies and land stocks satisfy the corresponding laws of motion (equations (C.48), (C.49), (C.50), and (C.51)) and land prices reflect future rents (equation (C.42)).

# D Details of Calibration

## D.1 Trade costs

Our calibration of trade costs follows a three step procedure. Recall that we parametrize trade costs as follows

$$d_{ij,g} = (1 + \kappa_{ij,g})\left(1 + t^{ice}_{ij,g}\right)\left(1 + t^{rev}_{ij,g}\right)$$

where $\kappa_{ij,g}$ is an iceberg trade cost unrelated to policy, $t^{ice}_{ij,g}$ is an iceberg trade cost generated by policy, and $t^{rev}_{ij,g}$ is a non-iceberg trade cost that generates revenues.

**Step 1 - Recover trade costs $d_{ij,g}$ from gravity equations.**

In the first step, we follow common practices in the empirical gravity literature and estimate the following regression:

$$\log(X_{ij,g}) = \alpha_{i,g} + \beta_{j,g} + \epsilon_{ij,g}$$

where $\alpha_{i,g}$ is an origin fixed effect, $\beta_{j,g}$ is a destination fixed effect and $\epsilon_{ij,g}$ is the residual. Here, the residual equals $(1-\sigma_g)\log(d_{ij,g})$. Assuming that $d_{ii,g}=1$, we recover $d_{ij,g}=exp\left(\widehat{\epsilon}_{ij,g}/\left(1-\sigma_g\right)\right)$, where $\widehat{\epsilon}_{ij,g}$ are the estimates of the residual term.

**Step 2 - Separate policy trade costs from non-policy trade costs.**

In the second step, we run regressions of $d_{ij,g}$ against observables related to policy barriers. We start by defining

$$d_{ij,g}=\underbrace{\tilde{d}_{ij,g}\exp\left(\gamma X_{ij,g}^{geography}\right)}_{\equiv(1+\kappa_{ij,g})}\underbrace{\exp\left(\beta X_{ij,g}^{policy}\right)}_{\equiv\left(1+t_{ij,g}^{ice}\right)\left(1+t_{ij,g}^{rev}\right)},$$

where $X_{ij,g}^{policy}$ are observables related to policy barriers and $X_{ij,g}^{geography}$ are observables related to geography. For convenience, we re-define the policy variables $X_{ij,g}^{policy}$ so that $X_{ij,g}^{policy}=0$ represents the "no-policy" barrier case.[40] Taking logs, we estimate

$$\log\left(d_{ij,g}\right)=\gamma X_{ij,g}^{geography}+\beta X_{ij,g}^{policy}+\log\left(\tilde{d}_{ij,g}\right)$$

which gives $\widehat{\gamma}$, $\widehat{\beta}$, and $\widehat{\log\left(\tilde{d}_{ij,g}\right)}$. Lastly, by setting $X_{ij,g}^{policy}=0$, we can recover the trade barriers that are unrelated to policy

$$(1+\kappa_{ij,g})=\exp\left(\widehat{\gamma}X_{ij,g}^{geography}+\log\left(\tilde{d}_{ij,g}\right)\right).$$

Using the above expression, we can recover the policy barriers as:

$$\left(1+t_{ij,g}^{ice}\right)\left(1+t_{ij,g}^{rev}\right)=\frac{d_{ij,g}}{(1+\kappa_{ij,g})}.$$

**Step 3 - Separate iceberg trade costs from non-icerberg trade costs generated by policy.**

In the third and final step, we make the assumption that $t_{ij,g}^{ice}$ is proportional to $t_{ij,g}^{rev}$

$$t_{ij,g}^{ice}=\omega_j t_{ij,g}^{rev}.$$

We calibrate $\omega_j$ so that the model matches, for each destination country, the tariff revenues per agricultural GDP observed in the data.

[40] For example, our "free trade agreement" dummy variable is defined as 1 if a country does not have a free-trade, and 0 otherwise.

# E Model validation

This section contains the details of four model validation exercises: (i) the role of fallow land, (ii) the model's ability to replicate our reduced-form facts, (iii) the correlation of deforestation productivity, $\zeta_i$, with empirical measures of forest protection, and (iv) the correlation of agricultural productivity in the model and the data.

**The fallow land module.** As discussed above, our model introduces a fallow land module, which allows for agricultural land expansions that do not come directly from deforestation. The figure plots the regression coefficients of forest area and of agricultural land on own population. The figure shows that the model cannot reproduce the responses of agricultural land in the absence of fallow land.

**The impact of foreign population growth.**

**Correlation of deforestation productivity and empirical measures of forest protection.**

**Implied agricultural productivity**

# F The impact of a 30-percent reduction in iceberg trade costs

We contrast now two counterfactual scenarios, both of them involving 30-percent reductions in iceberg agricultural trade costs. In the first scenario, we only reduce the trade costs faced by Brazil; in the second, we reduce trade costs globally. These results allow us to highlight the importance of general equilibrium adjustments, in light of Propositions 1 and 2.

**Business as usual.** We begin by reporting the frontier of cleared land in the business as usual (BAU) scenario—which is the baseline outcome of our model where no policy or shock is introduced. Panel (a) in Figure H.14 shows this path for select countries, as well as for the global economy. As a consequence of our approach to calibration, the land frontier remains almost constant across countries and globally.[41]

**Counterfactual #1: Reduction in Brazil's export costs.** We begin by considering a 30 percent reduction in iceberg trade costs of agricultural goods produced in Brazil.[42] As shown in Figure H.14, Panel (b) global forest area increases over time, but barely. Figure H.14, Panel (c) disaggregates this global trend into the experiences of selected individual countries, and Appendix Table H.3 presents the details. The reason global forest area grows is that, although Brazil's forest (as share of country area) drops by about 1 percentage points, regrowth in the rest of the world, dominates Brazil's response in the aggregate.

**Counterfactual #2: Global trade cost reductions.**

**#2: Global trade cost reductions.** Compare this outcome with that following a 30% reduction in trade costs of agricultural goods across all countries. In this case, the global forest share would grow by 2.5 percentage points in the steady state following the multilateral trade cost reduction.

The stark contrast between these two scenarios highlights a key message of our paper: global trade cost reductions can increase forest cover, which is the opposite of the impact of a trade cost reduction targeted to an individual country on its own forest. As highlighted in

[41] We emphasize that this baseline is not a forecast based on our model. In our baseline scenario, productivity, population, and land remain constant over time, while one would need to know their future paths to forecast the future of forests. In subsection 8.2, we incorporate population growth into an alternative BAU scenario and evaluate how it affects our quantitative conclusions.

[42] Specifically, we adjust the reductions in $\left(1 - t_{ij,g}^{ice}\right)$ and $\left(1 - t_{ij,g}^{rev}\right)$ by $(0.70)^{1/2}$ so that each term accounts for half of the 30% reduction in trade costs.

Propositions 1 and 2, this result follows because the elasticity of land demand at the country level is large—and driven by the trade elasticity—and that at the global level is small—and driven by the substitution between broad sectors of the economy.

Note also that in our counterfactual #2, there is wide dispersion in the responses across different countries (Figure H.14, Panel (d) and Appendix Table H.3). These responses reflect that in the aftermath of a global trade cost reduction, comparative advantage determines the specialization of countries across sectors. We return to this issue in more detail in our next exercise. Figure H.14, Panel (d) also shows that the average half-life of the shock across countries is 28 years: since (i) some countries tend to reforest and forest regrowth takes time, and (ii) the land use across countries is linked through international trade, deforestation cannot be too quick, resulting in a slow convergence to the steady state.

# G Computing the Social Cost of Carbon

This section shows how we compute the social cost of carbon in Section 8.3 using a simplified notation. First, suppose the global climate-adjusted welfare is:

$$W = V - \varphi Z, \qquad V = \prod_i \left(\frac{V_i}{\alpha_i}\right)^{\alpha_i}$$

where $V$ is the global indirect utility with $\alpha_i$ as the weight assigned to the indirect utility of country $i$, and $\varphi$ is the global damage from carbon emissions. It can be shown—see Appendix C in Farrokhi and Lashkaripour (2024)—that the globally-optimal carbon tax is:

$$\tau = P \times \varphi, \qquad P = \prod_i P_i^{\alpha_i}$$

where $P$ is the global price index. In practice, we pick $\alpha_i$ as the share of a country's population over global gross output at the initial year.

Since the globally first-best carbon tax must be equal to the social cost of carbon:

$$P \times \varphi = SCC$$

Given the above expression, and connecting the values in the model to those in the data by using the US GDP as the numeraire, we can recover $\varphi$ as:

$$\varphi = SCC^{data} \times \frac{Y_{USA}}{Y_{USA}^{data}} \times \frac{1}{P}$$

Adding time indices to climate-adjusted welfare, and taking differences between the equilibrium path under a policy scenario relative to the BAU:

$$\Delta W(t) = \Delta V(t) - \varphi \times \Delta Z(t)$$

From here:

$$\underbrace{\int e^{-\rho t} \Delta W(t)\, \mathrm{d}t}_{\Delta W} = \underbrace{\int e^{-\rho t} \Delta V(t)\, \mathrm{d}t}_{\Delta V} - \underbrace{\varphi \int e^{-\rho t} \Delta Z(t)\, \mathrm{d}t}_{\Delta D}.$$

The equation above gives the total change in welfare at the global level.

# H Additional Tables and Figures

Table H.1: Mapping of Countries to Regions

| ISO | Region | Individual Country |
|---|---|---|
| ARG | Argentina | ARG |
| AUS | Australia | AUS |
| BOL | Bolivia | BOL |
| BRA | Brazil | BRA |
| CAN | Canada | CAN |
| CHN | China | CHN |
| CMR | Cameroon | CMR |
| COL | Colombia | COL |
| DEU | Germany | DEU |
| ESP | Spain | ESP |
| ETH | Ethiopia | ETH |
| FIN | Finland | FIN |
| FRA | France | FRA |
| GBR | United Kingdom | GBR |
| IDN | Indonesia | IDN |
| IND | India | IND |
| ITA | Italy | ITA |
| JPN | Japan | JPN |
| MEX | Mexico | MEX |
| MOZ | Mozambique | MOZ |
| MYS | Malaysia | MYS |
| NGA | Nigeria | NGA |
| PER | Peru | PER |
| PRY | Paraguay | PRY |
| RUS | Russia | RUS |
| SWE | Sweden | SWE |
| THA | Thailand | THA |
| TUR | Turkey | TUR |
| TZA | Tanzania | TZA |
| USA | USA | USA |
| VEN | Venezuela | VEN |
| XAM | Rest of America | ABW, AIA, ATG, BES, BHS, BLM, BLZ, BMU, BRB, CHL CRI, CUB, CUW, CYM, DMA, DOM, ECU, FLK, GRD, GTM GUF, GUY, HND, HTI, JAM, KNA, LCA, MAF, MSR, NIC PAN, PRI, SJM, SLV, SPM, SUR, SXM, TCA, TTO, URY VCT, VGB, VIR |
| XAS | Rest of Asia | AFG, ASM, BGD, BRN, BTN, COK, FJI, FSM, GUM, HKG KAZ, KGZ, KHM, KIR, KOR, LAO, LKA, MDV, MHL, MMR MNG, MNP, NCL, NIU, NPL, NRU, NZL, PAK, PCN, PHL PLW, PNG, PRK, PYF, SGP, SLB, TJK, TKL, TKM, TLS TON, TUV, TWN, UZB, VNM, VUT, WLF, WSM |
| XCF | Central Africa | AGO, CAF, COD, COG, GAB, GNQ, RWA, STP, TCD |
| XEU | Rest of Europe | ALB, AND, AUT, BEL, BGR, BIH, BLR, CHE, CZE, DNK EST, FRO, GGY, GIB, GRC, HRV, HUN, IMN, IRL, ISL JEY, LIE, LTU, LUX, LVA, MCO, MDA, MKD, MLT, MNE NLD, NOR, POL, PRT, ROU, SMR, SRB, SVK, SVN, UKR VAT |
| XMN | Rest of Mena | ARE, ARM, AZE, BHR, CYP, DZA, EGY, ESH, GEO, IRN IRQ, ISR, JOR, KWT, LBN, LBY, MAR, OMN, PSE, QAT SAU, SYR, TUN, YEM |
| XOF | Other Africa | BDI, BWA, COM, DJI, ERI, KEN, LSO, MDG, MUS, MWI MYT, NAM, SDN, SOM, SSD, SWZ, SYC, UGA, ZAF |
| XWF | Rest of West Africa | BEN, BFA, CIV, CPV, GHA, GIN, GMB, GNB, LBR, MLI MRT, NER, SEN, SHN, SLE, TGO |
| ZMB | Zambia | ZMB |
| ZWE | Zimbabwe | ZWE |

Table H.2: Summary Statistics by Regions (1990-2020)

| | % of Global | % area in 1990 | | Change in Forest | | | % of Global |
|---|---|---|---|---|---|---|---|
| | Forest | Forest | Utilized | % | p.p. | Total | Deforestation |
| Country | (1) | (2) | (3) | (4) | (5). | (6) | (7) |
| Russia | 19.50 | 51 | 61 | 0.02 | 0.01 | 0.13 | -0.05 |
| Brazil | 14.33 | 68 | 99 | -17.07 | -11.68 | -99.94 | 34.32 |
| Canada | 8.41 | 39 | 45 | -4.33 | -1.68 | -14.89 | 5.11 |
| Central Africa | 7.54 | 60 | 70 | -13.44 | -8.01 | -41.36 | 14.21 |
| USA | 6.97 | 41 | 73 | -0.79 | -0.32 | -2.24 | 0.77 |
| Rest of Asia | 4.54 | 26 | 68 | -9.58 | -2.45 | -17.76 | 6.10 |
| Australia | 3.25 | 29 | 62 | -0.94 | -0.27 | -1.24 | 0.43 |
| Indonesia | 2.90 | 59 | 91 | -26.01 | -15.43 | -30.79 | 10.58 |
| China | 2.77 | 13 | 69 | 19.73 | 2.52 | 22.29 | -7.66 |
| Other Africa | 2.62 | 22 | 54 | -17.41 | -3.87 | -18.61 | 6.39 |
| Rest of America | 2.55 | 47 | 72 | -5.16 | -2.45 | -5.38 | 1.85 |
| Rest of West Africa | 1.91 | 18 | 41 | -21.50 | -3.86 | -16.78 | 5.76 |
| Peru | 1.87 | 66 | 75 | -6.49 | -4.29 | -4.94 | 1.70 |
| Rest of Europe | 1.79 | 25 | 77 | 5.56 | 1.41 | 4.07 | -1.40 |
| Mexico | 1.73 | 47 | 87 | -7.03 | -3.33 | -4.96 | 1.70 |
| Colombia | 1.59 | 69 | 99 | -9.48 | -6.58 | -6.15 | 2.11 |
| India | 1.43 | 15 | 87 | 1.15 | 0.17 | 0.67 | -0.23 |
| Bolivia | 1.41 | 68 | 82 | -12.14 | -8.31 | -7.01 | 2.41 |
| Tanzania | 1.39 | 64 | 100 | -20.49 | -13.06 | -11.65 | 4.00 |
| Venezuela | 1.26 | 63 | 82 | -13.04 | -8.27 | -6.73 | 2.31 |
| Zambia | 1.16 | 82 | 89 | -5.48 | -4.51 | -2.59 | 0.89 |
| Mozambique | 1.06 | 89 | 100 | -15.39 | -13.62 | -6.67 | 2.29 |
| Argentina | 0.84 | 14 | 56 | -21.20 | -2.92 | -7.30 | 2.51 |
| Sweden | 0.69 | 67 | 78 | -0.30 | -0.20 | -0.08 | 0.03 |
| Nigeria | 0.64 | 26 | 97 | -18.47 | -4.76 | -4.85 | 1.67 |
| Paraguay | 0.63 | 64 | 100 | -37.55 | -23.93 | -9.59 | 3.29 |
| Rest of Mena | 0.57 | 3 | 11 | 6.88 | 0.18 | 1.60 | -0.55 |
| Cameroon | 0.55 | 44 | 69 | -9.80 | -4.32 | -2.20 | 0.76 |
| Finland | 0.54 | 69 | 80 | 2.44 | 1.69 | 0.53 | -0.18 |
| Turkey | 0.47 | 26 | 76 | 11.78 | 3.07 | 2.27 | -0.78 |
| Ethiopia | 0.46 | 15 | 74 | -16.14 | -2.40 | -3.05 | 1.05 |
| Malaysia | 0.46 | 57 | 83 | -6.78 | -3.87 | -1.27 | 0.44 |
| Zimbabwe | 0.46 | 58 | 79 | -7.16 | -4.13 | -1.34 | 0.46 |
| Thailand | 0.43 | 30 | 82 | -7.40 | -2.25 | -1.31 | 0.45 |
| Japan | 0.36 | 47 | 81 | 0.60 | 0.28 | 0.09 | -0.03 |
| France | 0.32 | 22 | 83 | 14.69 | 3.26 | 1.92 | -0.66 |
| Spain | 0.29 | 27 | 87 | 33.64 | 9.13 | 4.02 | -1.38 |
| Italy | 0.17 | 22 | 85 | 26.34 | 5.75 | 1.86 | -0.64 |
| Germany | 0.14 | 15 | 85 | 1.05 | 0.16 | 0.06 | -0.02 |
| United Kingdom | 0.01 | 2 | 84 | 0.00 | 0.00 | 0.00 | 0.00 |
| World | 100.00 | 36 | 65 | -7.13 | -2.59 | -291.17 | 100.00 |

***Notes***: This table reports summary statistics of changes in forest area between 1990 and 2020 based on the Forest Resource Assessment report of 2020 from FAO. Column 1 is based on forest area as of 1990. Column 2 shows percentage change in forest area between 1990 and 2020. Column 3 shows percentage change in agricultural land use area year. Column 4 shows the share of global forest coming from each region.

Table H.3: Counterfactual Changes in Forest Area

| | | Baseline | | | Baseline + Pop. growth | | | |
|---|---|---|---|---|---|---|---|---|
| ISO | Region | BAU(pp) | C1(pp) | C2(pp) | BAU(pp) | C1(pp) | C2(pp) | Pop. growth(%) |
| ARG | Argentina | -0.00 | 0.08 | -0.33 | -1.33 | 0.07 | -0.26 | 39.3 |
| AUS | Australia | -0.00 | 0.31 | -1.65 | -7.91 | 0.28 | -1.58 | 94.6 |
| BOL | Bolivia | -0.00 | 0.14 | 0.52 | -7.25 | 0.13 | 0.56 | 73.1 |
| BRA | Brazil | -0.00 | -3.53 | -1.12 | 0.08 | -3.74 | -1.20 | -7.7 |
| CAN | Canada | -0.00 | 0.37 | -2.08 | -6.44 | 0.28 | -1.62 | 67.5 |
| CHN | China | -0.00 | 0.28 | 1.96 | 1.57 | 0.26 | 1.99 | -20.4 |
| CMR | Cameroon | -0.00 | 0.10 | -0.06 | -18.08 | 0.05 | 0.08 | 343.6 |
| COL | Colombia | -0.00 | 0.14 | 0.42 | -0.31 | 0.14 | 0.22 | -0.0 |
| DEU | Germany | -0.00 | 0.15 | -0.37 | -0.55 | 0.14 | -0.38 | -8.6 |
| ESP | Spain | -0.00 | 0.23 | -0.92 | 1.33 | 0.27 | -1.23 | -28.7 |
| ETH | Ethiopia | -0.00 | 0.02 | -0.01 | -5.40 | 0.01 | -0.04 | 235.9 |
| FIN | Finland | -0.00 | 0.32 | -0.87 | -0.18 | 0.30 | -0.94 | -2.0 |
| FRA | France | -0.00 | 0.23 | -0.41 | -1.71 | 0.22 | -0.83 | 3.0 |
| GBR | United Kingdom | 0.02 | 0.01 | -0.06 | -0.11 | 0.01 | -0.06 | 24.4 |
| IDN | Indonesia | -0.00 | 0.29 | 3.03 | -2.95 | 0.25 | 3.05 | 32.6 |
| IND | India | -0.00 | 0.05 | 1.57 | -0.91 | 0.05 | 1.61 | 17.2 |
| ITA | Italy | -0.00 | 0.19 | -0.31 | 2.08 | 0.20 | -0.65 | -32.5 |
| JPN | Japan | -0.00 | 0.19 | 1.19 | 6.89 | 0.26 | 0.98 | -41.5 |
| MEX | Mexico | -0.00 | 0.17 | 0.14 | -2.43 | 0.15 | 0.14 | 24.0 |
| MOZ | Mozambique | -0.00 | 0.84 | 5.33 | -22.73 | 0.47 | 3.86 | 425.5 |
| MYS | Malaysia | -0.00 | 0.20 | 0.32 | -3.78 | 0.17 | 0.35 | 42.1 |
| NGA | Nigeria | -0.00 | 0.00 | 0.07 | -10.83 | 0.00 | 0.04 | 362.4 |
| PER | Peru | -0.00 | 0.06 | 1.32 | -3.43 | 0.06 | 1.39 | 34.9 |
| PRY | Paraguay | -0.00 | 0.15 | -1.05 | -4.46 | 0.16 | -0.82 | 39.8 |
| RUS | Russia | -0.00 | 0.29 | 1.13 | -0.32 | 0.30 | 0.44 | -11.7 |
| SWE | Sweden | -0.00 | 0.34 | -2.43 | -4.68 | 0.38 | -2.54 | 38.9 |
| THA | Thailand | -0.00 | 0.36 | 0.70 | 3.85 | 0.33 | 0.54 | -31.5 |
| TUR | Turkey | -0.00 | 0.21 | 0.56 | -2.00 | 0.20 | 0.34 | 19.1 |
| TZA | Tanzania | -0.00 | 0.04 | 1.45 | -23.94 | 0.03 | 0.93 | 544.1 |
| USA | USA | -0.00 | 0.31 | -1.01 | -2.82 | 0.23 | -0.87 | 40.3 |
| VEN | Venezuela | -0.00 | 0.26 | 1.02 | -2.29 | 0.23 | 1.01 | 20.4 |
| XAM | Rest of America | -0.00 | 0.21 | -0.16 | -2.69 | 0.18 | -0.13 | 29.3 |
| XAS | Rest of Asia | -0.00 | 0.16 | 1.63 | -2.39 | 0.14 | 1.64 | 49.6 |
| XCF | Central Africa | -0.00 | 0.43 | 4.25 | -21.05 | 0.28 | 3.04 | 468.1 |
| XEU | Rest of Europe | -0.00 | 0.16 | 0.05 | 0.94 | 0.18 | -0.37 | -26.0 |
| XMN | Rest of Mena | -0.00 | 0.09 | 1.21 | -2.39 | 0.07 | 0.91 | 98.7 |
| XOF | Other Africa | -0.00 | 0.07 | 1.31 | -6.29 | 0.04 | 0.76 | 249.8 |
| XWF | Rest of West Africa | -0.00 | 0.07 | 0.17 | -9.64 | 0.03 | 0.12 | 405.5 |
| ZMB | Zambia | -0.00 | 0.05 | -0.31 | -25.61 | 0.04 | -0.47 | 499.3 |
| ZWE | Zimbabwe | -0.00 | 0.12 | 0.94 | -11.67 | 0.12 | 0.81 | 143.9 |
| World | | -0.00 | -0.07 | 0.55 | -3.97 | -0.12 | 0.35 | 40.0 |

***Notes***: Columns 1 to 3 report results from our first baseline scenario (in percentage points). Column "BAU" reports the change in steady state relative to time 0; Columns "C1" and "C2" report the steady state change in each counterfactual, relative to the steady state in BAU. Columns 4 to 6 repeat the same results, for the baseline scenario that includes population growth. The last column contains the changes in population we feed into the model, in percentage terms relative to time 0.

Table H.4: Summary Statistics by Country (1990-2020) - First Part

| | % of Global | % area in 1990 | | Change in Forest | | | % of Global |
|---|---|---|---|---|---|---|---|
| | Forest | Forest | Utilized | % | p.p. | Total | Deforestation |
| Country | (1) | (2) | (3) | (4) | (5). | (6) | (7) |
| Russia | 19.50 | 51 | 61 | 0.02 | 0.01 | 0.13 | -0.05 |
| Brazil | 14.33 | 68 | 99 | -17.07 | -11.68 | -99.94 | 34.32 |
| Canada | 8.41 | 39 | 45 | -4.33 | -1.68 | -14.89 | 5.11 |
| USA | 6.97 | 41 | 73 | -0.79 | -0.32 | -2.24 | 0.77 |
| DRC | 3.69 | 70 | 77 | -16.26 | -11.40 | -24.48 | 8.41 |
| Australia | 3.25 | 29 | 62 | -0.94 | -0.27 | -1.24 | 0.43 |
| Indonesia | 2.90 | 59 | 91 | -26.01 | -15.43 | -30.79 | 10.58 |
| China | 2.77 | 13 | 69 | 19.73 | 2.52 | 22.29 | -7.66 |
| Angola | 1.92 | 92 | 100 | -15.97 | -14.76 | -12.50 | 4.29 |
| Peru | 1.87 | 66 | 75 | -6.49 | -4.29 | -4.94 | 1.70 |
| Mexico | 1.73 | 47 | 87 | -7.03 | -3.33 | -4.96 | 1.70 |
| Colombia | 1.59 | 69 | 99 | -9.48 | -6.58 | -6.15 | 2.11 |
| India | 1.43 | 15 | 87 | 1.15 | 0.17 | 0.67 | -0.23 |
| Bolivia | 1.41 | 68 | 82 | -12.14 | -8.31 | -7.01 | 2.41 |
| Tanzania | 1.39 | 64 | 100 | -20.49 | -13.06 | -11.65 | 4.00 |
| Venezuela | 1.26 | 63 | 82 | -13.04 | -8.27 | -6.73 | 2.31 |
| Zambia | 1.16 | 82 | 89 | -5.48 | -4.51 | -2.59 | 0.89 |
| Mozambique | 1.06 | 89 | 100 | -15.39 | -13.62 | -6.67 | 2.29 |
| Myanmar | 0.96 | 47 | 81 | -28.25 | -13.17 | -11.07 | 3.80 |
| Papua New Guinea | 0.89 | 79 | 83 | -1.50 | -1.19 | -0.54 | 0.19 |
| Argentina | 0.84 | 14 | 56 | -21.20 | -2.92 | -7.30 | 2.51 |
| Central Africa | 0.81 | 28 | 47 | -3.71 | -1.06 | -1.22 | 0.42 |
| Sweden | 0.69 | 67 | 78 | -0.30 | -0.20 | -0.08 | 0.03 |
| Nigeria | 0.64 | 26 | 97 | -18.47 | -4.76 | -4.85 | 1.67 |
| Paraguay | 0.63 | 64 | 100 | -37.55 | -23.93 | -9.59 | 3.29 |
| Gabon | 0.58 | 98 | 100 | -0.97 | -0.95 | -0.23 | 0.08 |
| Sudan | 0.57 | 14 | 48 | -22.26 | -3.20 | -5.22 | 1.79 |
| Cameroon | 0.55 | 44 | 69 | -9.80 | -4.32 | -2.20 | 0.76 |
| Republic of Congo | 0.54 | 91 | 95 | -1.66 | -1.51 | -0.37 | 0.13 |
| Finland | 0.54 | 69 | 80 | 2.44 | 1.69 | 0.53 | -0.18 |
| Turkey | 0.47 | 26 | 76 | 11.78 | 3.07 | 2.27 | -0.78 |
| Ethiopia | 0.46 | 15 | 74 | -16.14 | -2.40 | -3.05 | 1.05 |
| Botswana | 0.46 | 57 | 64 | -18.87 | -10.69 | -3.55 | 1.22 |
| Malaysia | 0.46 | 57 | 83 | -6.78 | -3.87 | -1.27 | 0.44 |
| Zimbabwe | 0.46 | 58 | 79 | -7.16 | -4.13 | -1.34 | 0.46 |
| Guyana | 0.46 | 97 | 100 | -1.00 | -0.97 | -0.19 | 0.06 |
| Thailand | 0.43 | 30 | 82 | -7.40 | -2.25 | -1.31 | 0.45 |
| South Africa | 0.40 | 7 | 17 | -6.04 | -0.40 | -0.99 | 0.34 |
| Laos | 0.40 | 71 | 84 | -8.70 | -6.16 | -1.41 | 0.49 |
| Suriname | 0.38 | 97 | 99 | -1.19 | -1.15 | -0.18 | 0.06 |
| Japan | 0.36 | 47 | 81 | 0.60 | 0.28 | 0.09 | -0.03 |
| Ecuador | 0.36 | 56 | 80 | -15.09 | -8.43 | -2.20 | 0.76 |
| Mongolia | 0.35 | 30 | 69 | -1.27 | -0.38 | -0.18 | 0.06 |
| Chile | 0.33 | 22 | 31 | 10.49 | 2.28 | 1.43 | -0.49 |
| Madagascar | 0.33 | 42 | 75 | -9.99 | -4.16 | -1.34 | 0.46 |
| Mali | 0.33 | 13 | 23 | -4.24 | -0.57 | -0.56 | 0.19 |
| France | 0.32 | 22 | 83 | 14.80 | 3.27 | 1.91 | -0.66 |
| Norway | 0.30 | 32 | 38 | -0.49 | -0.16 | -0.06 | 0.02 |
| Spain | 0.29 | 27 | 87 | 33.64 | 9.13 | 4.02 | -1.38 |
| Mena | 0.29 | 3 | 14 | 11.47 | 0.38 | 1.34 | -0.46 |
| Cambodia | 0.27 | 58 | 88 | -31.75 | -18.57 | -3.47 | 1.19 |
| Ghana | 0.24 | 49 | 99 | -22.13 | -10.94 | -2.19 | 0.75 |
| Senegal | 0.23 | 53 | 94 | -13.32 | -7.06 | -1.23 | 0.42 |
| Poland | 0.22 | 27 | 91 | 6.77 | 1.86 | 0.60 | -0.21 |
| Namibia | 0.21 | 19 | 26 | -24.29 | -4.54 | -2.13 | 0.73 |
| Vietnam | 0.21 | 21 | 60 | 19.27 | 4.05 | 1.66 | -0.57 |
| Liberia | 0.21 | 95 | 100 | -10.95 | -10.42 | -0.93 | 0.32 |
| Somalia | 0.20 | 34 | 56 | -27.81 | -9.51 | -2.30 | 0.79 |
| Other South America | 0.20 | 96 | 98 | -1.50 | -1.44 | -0.12 | 0.04 |
| Cote Divoire | 0.19 | 30 | 81 | -64.01 | -19.41 | -5.02 | 1.72 |
| New Zealand | 0.19 | 35 | 97 | -0.42 | -0.15 | -0.03 | 0.01 |
| Burkina Faso | 0.19 | 24 | 68 | -21.59 | -5.24 | -1.66 | 0.57 |
| Phillipines | 0.18 | 22 | 68 | -9.08 | -2.00 | -0.68 | 0.23 |
| Guinea | 0.18 | 33 | 86 | -15.26 | -4.98 | -1.10 | 0.38 |
| Italy | 0.17 | 22 | 85 | 26.34 | 5.75 | 1.86 | -0.64 |
| Honduras | 0.17 | 60 | 92 | -8.99 | -5.44 | -0.63 | 0.22 |
| Chad | 0.16 | 6 | 32 | -36.11 | -2.31 | -2.43 | 0.83 |
| Belarus | 0.16 | 36 | 84 | -0.32 | -0.11 | -0.02 | 0.01 |
| Nicaragua | 0.16 | 50 | 87 | -47.78 | -23.90 | -3.06 | 1.05 |
| Romania | 0.14 | 28 | 91 | 3.27 | 0.91 | 0.19 | -0.07 |
| North Korea | 0.14 | 47 | 79 | -12.79 | -5.98 | -0.74 | 0.25 |
| Germany | 0.14 | 15 | 85 | 1.05 | 0.16 | 0.06 | -0.02 |
| Nepal | 0.14 | 27 | 78 | 2.82 | 0.76 | 0.16 | -0.05 |
| Morocco | 0.13 | 20 | 67 | -1.15 | -0.22 | -0.06 | 0.02 |
| Oceania | 0.13 | 61 | 74 | 1.35 | 0.83 | 0.07 | -0.02 |

Table H.5: Summary Statistics by Country (1990-2020) - Second Part

| | % of Global | % area in 1990 | | Change in Forest | | | % of Global |
|---|---|---|---|---|---|---|---|
| | Forest | Forest | Utilized | % | p.p. | Total | Deforestation |
| Country | (1) | (2) | (3) | (4) | (5). | (6) | (7) |
| Benin | 0.12 | 35 | 70 | -35.47 | -12.35 | -1.71 | 0.59 |
| Guatemala | 0.12 | 38 | 87 | -29.04 | -10.97 | -1.38 | 0.47 |
| Pakistan | 0.12 | 4 | 68 | -26.64 | -1.09 | -1.26 | 0.43 |
| Ukraine | 0.12 | 9 | 87 | 2.87 | 0.27 | 0.13 | -0.05 |
| South Korea | 0.11 | 44 | 91 | -13.32 | -5.85 | -0.62 | 0.21 |
| Panama | 0.11 | 65 | 90 | -9.75 | -6.31 | -0.45 | 0.15 |
| Turkmenistan | 0.10 | 24 | 57 | 0.00 | 0.00 | 0.00 | 0.00 |
| Balkans | 0.10 | 33 | 84 | 26.07 | 8.64 | 1.06 | -0.36 |
| Kenya | 0.09 | 7 | 50 | -6.68 | -0.47 | -0.25 | 0.08 |
| Uganda | 0.08 | 13 | 82 | -45.01 | -6.04 | -1.53 | 0.53 |
| Portugal | 0.08 | 39 | 79 | -2.56 | -1.01 | -0.09 | 0.03 |
| Malawi | 0.08 | 32 | 84 | -35.59 | -11.45 | -1.20 | 0.41 |
| Greece | 0.08 | 30 | 97 | 18.30 | 5.48 | 0.58 | -0.20 |
| Sierra Leone | 0.08 | 52 | 79 | -19.44 | -10.13 | -0.61 | 0.21 |
| Costa Rica | 0.07 | 57 | 100 | 2.34 | 1.33 | 0.07 | -0.02 |
| Latvia | 0.07 | 51 | 91 | 3.03 | 1.53 | 0.09 | -0.03 |
| Georgia | 0.07 | 44 | 84 | 1.93 | 0.86 | 0.05 | -0.02 |
| Kazakhstan | 0.06 | 3 | 49 | 14.69 | 0.43 | 0.39 | -0.13 |
| Czech Republic | 0.06 | 26 | 87 | 1.81 | 0.48 | 0.05 | -0.02 |
| Bhutan | 0.06 | 53 | 63 | 8.72 | 4.66 | 0.22 | -0.07 |
| Serbia | 0.06 | 24 | 89 | 14.64 | 3.45 | 0.33 | -0.11 |
| Guinea-Bissau | 0.05 | 69 | 100 | -11.37 | -7.89 | -0.25 | 0.09 |
| Bosnia | 0.05 | 49 | 84 | -1.00 | -0.49 | -0.02 | 0.01 |
| Sri Lanka | 0.05 | 29 | 78 | -11.00 | -3.21 | -0.23 | 0.08 |
| Austria | 0.05 | 29 | 79 | 9.37 | 2.72 | 0.19 | -0.07 |
| Estonia | 0.05 | 47 | 85 | 10.54 | 4.92 | 0.21 | -0.07 |
| Niger | 0.05 | 2 | 20 | -49.54 | -0.82 | -0.94 | 0.32 |
| Bangladesh | 0.05 | 5 | 98 | -6.49 | -0.30 | -0.12 | 0.04 |
| Hungary | 0.04 | 20 | 92 | 13.18 | 2.64 | 0.24 | -0.08 |
| Croatia | 0.04 | 31 | 77 | 6.42 | 1.97 | 0.11 | -0.04 |
| Cuba | 0.04 | 17 | 81 | 58.35 | 9.65 | 1.00 | -0.34 |
| Belize | 0.04 | 68 | 76 | -20.23 | -13.80 | -0.32 | 0.11 |
| Dominican Republic | 0.04 | 27 | 88 | 24.16 | 6.46 | 0.38 | -0.13 |
| Lithuania | 0.04 | 26 | 84 | 3.65 | 0.95 | 0.06 | -0.02 |
| Uzbekistan | 0.03 | 4 | 61 | 4.92 | 0.22 | 0.07 | -0.02 |
| Togo | 0.03 | 27 | 82 | -14.34 | -3.86 | -0.19 | 0.07 |
| West Africa | 0.03 | 2 | 6 | -16.68 | -0.30 | -0.20 | 0.07 |
| Afghanistan | 0.03 | 3 | 34 | 0.00 | 0.00 | 0.00 | 0.00 |
| Slovakia | 0.03 | 29 | 88 | 1.17 | 0.34 | 0.01 | -0.00 |
| Eritrea | 0.03 | 16 | 78 | -11.25 | -1.84 | -0.13 | 0.04 |
| West Europe | 0.03 | 23 | 71 | 14.38 | 3.36 | 0.15 | -0.05 |
| Kyrgyzstan | 0.02 | 9 | 29 | 11.12 | 0.97 | 0.11 | -0.04 |
| Timor Leste | 0.02 | 63 | 86 | -4.36 | -2.76 | -0.04 | 0.01 |
| Caribbean | 0.02 | 42 | 61 | -1.89 | -0.79 | -0.02 | 0.01 |
| Macedonia | 0.02 | 41 | 86 | 9.81 | 4.05 | 0.09 | -0.03 |
| Albania | 0.02 | 28 | 70 | 0.01 | 0.00 | 0.00 | -0.00 |
| El Salvador | 0.02 | 25 | 100 | -20.13 | -5.08 | -0.14 | 0.05 |
| Azerbaijan | 0.02 | 10 | 57 | 26.74 | 2.59 | 0.17 | -0.06 |
| Uruguay | 0.01 | 4 | 87 | 42.21 | 1.81 | 0.25 | -0.09 |
| Denmark | 0.01 | 10 | 87 | 18.25 | 1.89 | 0.10 | -0.03 |
| Jamaica | 0.01 | 45 | 92 | 14.83 | 6.68 | 0.08 | -0.03 |
| Tunisia | 0.01 | 4 | 49 | -0.57 | -0.03 | -0.00 | 0.00 |
| Gambia | 0.01 | 31 | 99 | -41.66 | -13.02 | -0.17 | 0.06 |
| Brunei | 0.01 | 76 | 81 | -9.04 | -6.90 | -0.04 | 0.01 |
| Haiti | 0.01 | 10 | 80 | -15.00 | -1.44 | -0.06 | 0.02 |
| Netherlands | 0.01 | 6 | 81 | 7.00 | 0.42 | 0.02 | -0.01 |
| United Kingdom | 0.01 | 2 | 84 | 0.00 | 0.00 | 0.00 | 0.00 |
| Armenia | 0.01 | 13 | 44 | -3.43 | -0.46 | -0.01 | 0.00 |
| Puerto Rico | 0.01 | 27 | 89 | 54.94 | 14.91 | 0.18 | -0.06 |
| Swaziland | 0.01 | 27 | 98 | 33.06 | 9.06 | 0.10 | -0.03 |
| Tajikistan | 0.01 | 3 | 22 | 3.77 | 0.10 | 0.01 | -0.00 |
| Belgium | 0.01 | 5 | 77 | 8.70 | 0.44 | 0.02 | -0.01 |
| Libya | 0.01 | 0 | 2 | 0.00 | 0.00 | 0.00 | 0.00 |
| Rwanda | 0.00 | 5 | 93 | -38.24 | -1.96 | -0.08 | 0.03 |
| East Africa | 0.00 | 25 | 76 | -4.87 | -1.23 | -0.01 | 0.00 |
| Moldova | 0.00 | 6 | 87 | -6.31 | -0.38 | -0.01 | 0.00 |
| Ireland | 0.00 | 1 | 90 | 32.68 | 0.34 | 0.03 | -0.01 |
| Egypt | 0.00 | 0 | 9 | 2.67 | 0.00 | 0.00 | -0.00 |
| Central America | 0.00 | 36 | 76 | -3.32 | -1.19 | -0.00 | 0.00 |
| Lesotho | 0.00 | 2 | 57 | 0.00 | 0.00 | 0.00 | 0.00 |
| Singapore | 0.00 | 15 | 48 | 5.01 | 0.77 | 0.00 | -0.00 |
| Iceland | 0.00 | 0 | 4 | 12.18 | 0.02 | 0.00 | -0.00 |
| Djibouti | 0.00 | 0 | 15 | 0.00 | 0.00 | 0.00 | 0.00 |
| Maldives | 0.00 | 3 | 30 | 0.00 | 0.00 | 0.00 | 0.00 |
| Other Northern Europe | 0.00 | 0 | 5 | 0.00 | 0.00 | 0.00 | 0.00 |
| World | 100.00 | 36 | 65 | -7.13 | -2.58 | -291.17 | 100.00 |

Table H.6: The Relationship between Population Growth and Forest Area (30 years interval)

| | OLS | OLS | OLS | IV | IV | IV |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| *a. DV is the log of forest area* | | | | | | |
| $s^{\text{Own}} \times \Delta$ Log(Own Pop) | -0.428*** | -0.450*** | -0.349*** | -0.516*** | -0.523*** | -0.391*** |
| | (0.061) | (0.064) | (0.071) | (0.061) | (0.063) | (0.076) |
| $s^{\text{Partner}} \times \Delta$ Log(Partner Pop) | -0.655*** | -0.849*** | -0.624*** | -0.850*** | -0.982*** | -0.694*** |
| | (0.223) | (0.209) | (0.220) | (0.237) | (0.216) | (0.251) |
| R2 or K-P | 0.290 | 0.329 | 0.361 | 67.828 | 69.616 | 49.170 |
| Obs | 150 | 150 | 150 | 150 | 150 | 150 |
| *b. DV is the log of agricultural area* | | | | | | |
| $s^{\text{Own}} \times \Delta$ Log(Own Pop) | 1.124*** | 1.096*** | 0.818*** | 1.211*** | 1.172*** | 0.647*** |
| | (0.099) | (0.105) | (0.114) | (0.098) | (0.102) | (0.125) |
| $s^{\text{Partner}} \times \Delta$ Log(Partner Pop) | 1.626*** | 1.575*** | 0.843 | 1.960*** | 1.883*** | 0.629 |
| | (0.530) | (0.532) | (0.569) | (0.605) | (0.607) | (0.609) |
| R2 or K-P | 0.464 | 0.474 | 0.542 | 67.828 | 69.616 | 49.170 |
| Obs | 150 | 150 | 150 | 150 | 150 | 150 |
| Controls (Initial period value in logs) | | | | | | |
| - Share of Agricultural area | - | Y | Y | - | Y | Y |
| - Share of Forest area | - | Y | Y | - | Y | Y |
| - Natural reserve area | - | - | Y | - | - | Y |
| - GDP p.c. | - | - | Y | - | - | Y |

**NNotes**: * / ** / *** denotes significance at the 10 / 5 / 1 percent level. Robust standard errors clustered at the country level in parenthesis. Instrument in columns (4) to (6) are (1) the log of the median age of the population, (2) the birth rate, and (3) the average age of child bearing in the baseline year. Kleinberg-Paap weak instrument statistic is reported in columns (4) to (6) instead of R2.

Table H.7: The Relationship between Population Growth and Fallow Land (30 years interval)

| | OLS | OLS | OLS | IV | IV | IV |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| *a. DV is the log of fallow land* | | | | | | |
| $s^{\text{Own}} \times \Delta$ Log(Own Pop) | 0.551 | 0.757** | 0.613 | 0.505 | 0.646** | 0.150 |
| | (0.407) | (0.368) | (0.591) | (0.348) | (0.304) | (0.702) |
| $s^{\text{Partner}} \times \Delta$ Log(Partner Pop) | 8.973** | 9.366*** | 9.114*** | 8.521** | 9.054*** | 8.429*** |
| | (3.628) | (3.251) | (3.175) | (3.339) | (2.847) | (2.958) |
| R2 or K-P | 0.167 | 0.332 | 0.336 | 34.995 | 32.726 | 12.313 |
| Obs | 40 | 40 | 40 | 40 | 40 | 40 |
| Controls (Initial period value in logs) | | | | | | |
| - Share of Agricultural area | - | Y | Y | - | Y | Y |
| - Share of Forest area | - | Y | Y | - | Y | Y |
| - Natural reserve area | - | - | Y | - | - | Y |
| - GDP p.c. | - | - | Y | - | - | Y |

**Notes**: * / ** / *** denotes significance at the 10 / 5 / 1 percent level. Robust standard errors clustered at the country level in parenthesis. Instrument in columns (4) to (6) are (1) the log of the median age of the population, (2) the birth rate, and (3) the average age of child bearing in the baseline year. Kleinberg-Paap weak instrument statistic is reported in columns (4) to (6) instead of R2.

Table H.8: Domestic vs Foreign Pop Shock

| | Data | Model |
|---|---|---|
| | (1) | (2) |
| *a. DV is the log of forest area* | | |
| Δ Log(Own Pop) | -0.408*** | -0.470*** |
| | (0.084) | (0.088) |
| Δ Log(Top Destination Pop) | -1.295* | -1.686** |
| | (0.711) | (0.825) |
| R2 or K-P | 32.726 | 0.844 |
| Obs | 40 | 40 |
| *b. DV is the log of agricultural area* | | |
| Δ Log(Own Pop) | 1.375*** | 0.748*** |
| | (0.102) | (0.038) |
| Δ Log(Top Destination Pop) | 3.632*** | 2.446*** |
| | (0.913) | (0.499) |
| R2 or K-P | 32.726 | 0.972 |
| Obs | 40 | 40 |
| Controls (Initial period value in logs) | | |
| - Share of Agricultural area | Y | Y |
| - Share of Forest area | Y | Y |

**Notes**: * / ** / *** denotes significance at the 10 / 5 / 1 percent level. Robust standard errors clustered at the country level in parenthesis. Column (1) shows the reduced-form impact of population growth in the actual data, as reported in our Empirical Fact 4. Column (2) presents the reduced-form impact of population growth using the data generated by our model when we introduce the population growth projected by United Nations.

Table H.9: Costs and Benefits of A 10x Hike in Agricultural Tariffs

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| *Panel A: Brazil* | | | | |
| Environmental Costs (as fraction of US GDP) | 0.000 | 0.639 | -1.142 | -5.712 |
| Welfare gains (percentual change) | -0.126 | -0.129 | -0.014 | 0.007 |
| *Panel B: All countries* | | | | |
| Environmental Costs (as fraction of US GDP) | 0.000 | 5.942 | 0.770 | 3.849 |
| Welfare gains (percentual change) | -0.199 | -0.229 | -0.225 | -0.243 |
| *Panel C: All countries ($\sigma = 1.5$)* | | | | |
| Environmental Costs (as fraction of US GDP) | 0.000 | -5.794 | -21.297 | -106.484 |
| Welfare gains (percentual change) | 1.185 | 1.204 | 1.771 | 2.056 |
| *Economic Assumptions* | | | | |
| - SCC = 0 | Y | - | - | - |
| - SCC = 200 | - | Y | Y | - |
| - SCC = 1000 | - | - | - | Y |
| - Population Growth | - | - | Y | Y |

Table H.10: SSC - Tariff to 0 - No sequestration

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| *Panel A: Brazil* | | | | |
| Environmental Costs (as fraction of US GDP) | 0.000 | 1.977 | 2.758 | 13.790 |
| Welfare gains (percentual change) | -0.090 | -0.100 | 0.000 | -0.052 |
| | | | | |
| *Panel B: All countries* | | | | |
| Environmental Costs (as fraction of US GDP) | 0.000 | 8.788 | 2.592 | 12.958 |
| Welfare gains (percentual change) | 0.131 | 0.086 | 0.167 | 0.121 |
| | | | | |
| *Panel C: All countries ($\sigma = 1.5$)* | | | | |
| Environmental Costs (as fraction of US GDP) | 0.000 | 31.199 | 31.941 | 159.704 |
| Welfare gains (percentual change) | 1.267 | 1.165 | -0.067 | -0.443 |
| *Economic Assumptions* | | | | |
| - SCC = 0 | Y | - | - | - |
| - SCC = 200 | - | Y | Y | - |
| - SCC = 1000 | - | - | - | Y |
| - Population Growth | - | - | Y | Y |

Table H.11: Costs and Benefits of Eliminating Agricultural Tariffs with Low Persistence

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| *Panel A: Brazil* | | | | |
| Environmental Costs (as fraction of US GDP) | 0.000 | 1.067 | 1.155 | 5.776 |
| Welfare gains (percentual change) | 0.014 | 0.008 | 0.007 | -0.014 |
| | | | | |
| *Panel B: All countries ($\sigma = 0.5$)* | | | | |
| Environmental Costs (as fraction of US GDP) | 0.000 | 7.055 | 0.743 | 3.713 |
| Welfare gains (percentual change) | 0.125 | 0.089 | 0.171 | 0.160 |
| | | | | |
| *Panel C: All countries ($\sigma = 1.5$)* | | | | |
| Environmental Costs (as fraction of US GDP) | 0.000 | 42.163 | 47.381 | 236.907 |
| Welfare gains (percentual change) | 0.016 | -0.124 | -0.109 | -0.674 |
| *Economic Assumptions* | | | | |
| - SCC = 0 | Y | - | - | - |
| - SCC = 200 | - | Y | Y | - |
| - SCC = 1000 | - | - | - | Y |
| - Population Growth | - | - | Y | Y |

**Notes**: This table replicates results from Table 3 using a low value for $\lambda$ of 0.2, which translate into weaker persistence in the costs of producing cleared land in the model.

Table H.12: Exploring Dynamics Considerations

| | Consider only periods t and below | | | | |
|---|---|---|---|---|---|
| | 5 | 10 | 20 | 50 | 200 |
| | (1) | (2) | (3) | (4) | (5) |
| *Panel A: Brazil* | | | | | |
| Environmental Costs (as fraction of US GDP) | 0.006 | -0.007 | -0.017 | -0.021 | -0.021 |
| Welfare gains (percentual change) | -0.082 | -0.086 | -0.088 | -0.089 | -0.090 |
| | | | | | |
| *Panel B: All countries ($\sigma = 0.5$)* | | | | | |
| Environmental Costs (as fraction of US GDP) | 0.001 | 0.049 | 0.085 | 0.100 | 0.101 |
| Welfare gains (percentual change) | 0.134 | 0.132 | 0.131 | 0.131 | 0.131 |
| *Economic Assumptions* | | | | | |
| - SCC = 200 | Y | Y | Y | Y | |
| - Population Growth | - | - | - | - | |

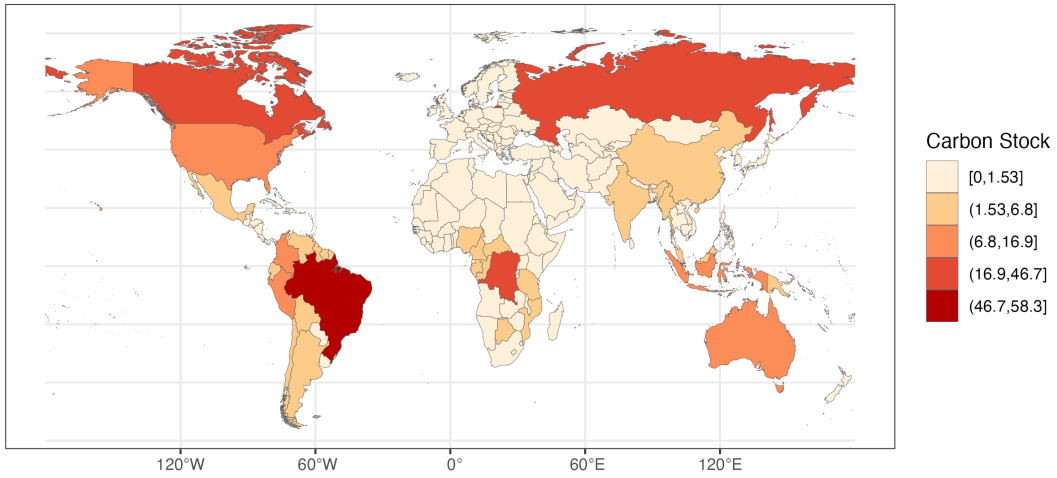
**Notes**: This table shows the cost and benefit analysis when we compute the welfare gains and environmental costs using different discounting schemes. Column (1) ignores any time period beyond the fifth year—i.e., we set the discount rate to 100 percent for any year after $t = 5$. Columns (2) to (5) shows how our conclusions change as we add additional time periods.

Table H.13: Deforestation over Time with Non-homothetic Preferences

| | (1) | (2) |
|---|---|---|
| *Panel A: t = 10* | | |
| Brazil only reduction | -0.004 | -0.003 |
| Global reduction | 0.148 | 0.150 |
| | | |
| *Panel B: t = 50* | | |
| Brazil only reduction | -0.144 | -0.140 |
| Global reduction | 0.288 | 0.294 |
| | | |
| *Panel C: t = SS* | | |
| Brazil only reduction | -0.267 | -0.262 |
| Global reduction | 0.489 | 0.501 |
| *Preference* | | |
| - Non-homothetic CES | - | Y |

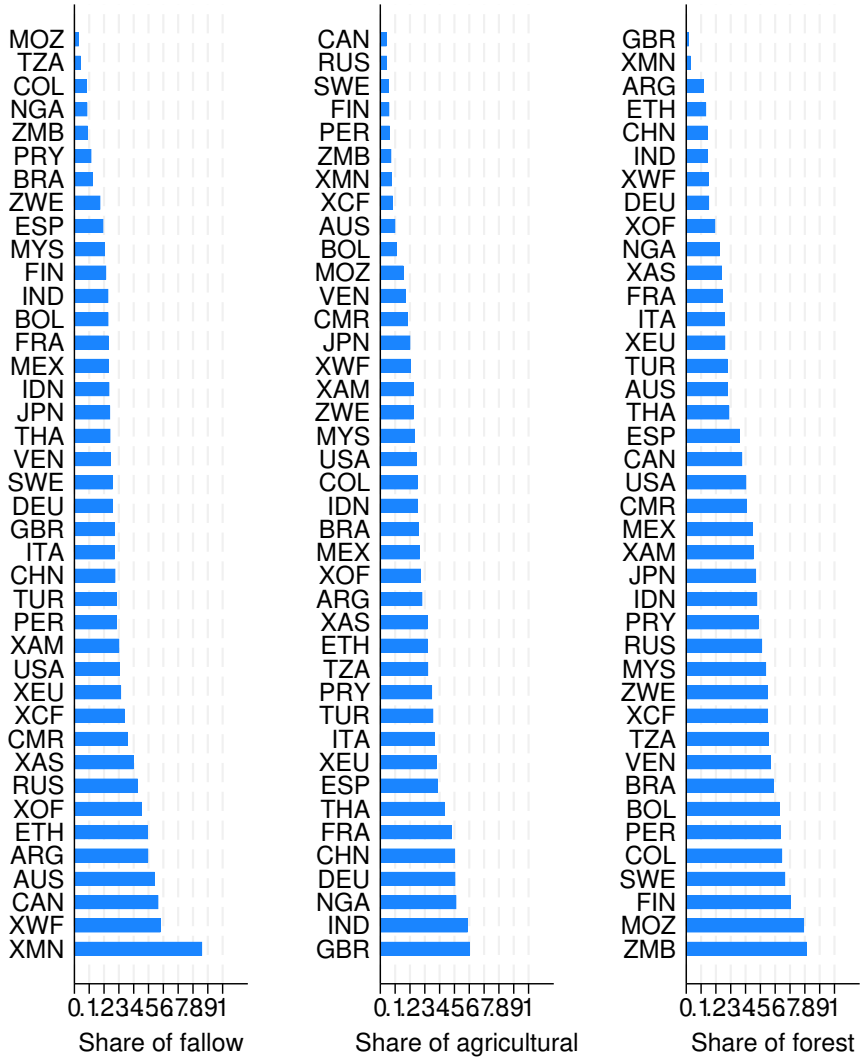
**Notes**: This table shows the changes in global deforestation when we consider non-homothetic preferences.

Figure H.1: Carbon Stock per Hectare across the World




**Notes**: This figure shows, for each country, the carbon content of forests, measured as tons of carbon per hectare of forest, which we use to compute the $CO_2$ emissions from deforestation. Data comes from FRA-FAO.

Figure H.2: Share of Land Allocated to each broad Category




***Notes***: This figure shows the share of land allocated to different types of uses in the 40 regions included in our data. Agricultural land includes both pasture and crop land. Fallow land is the total area of the country minus area under forest and agriculture. Total area of a country excludes water surface or other non-productive.

Figure H.3: Graphical Representation of Proposition 4

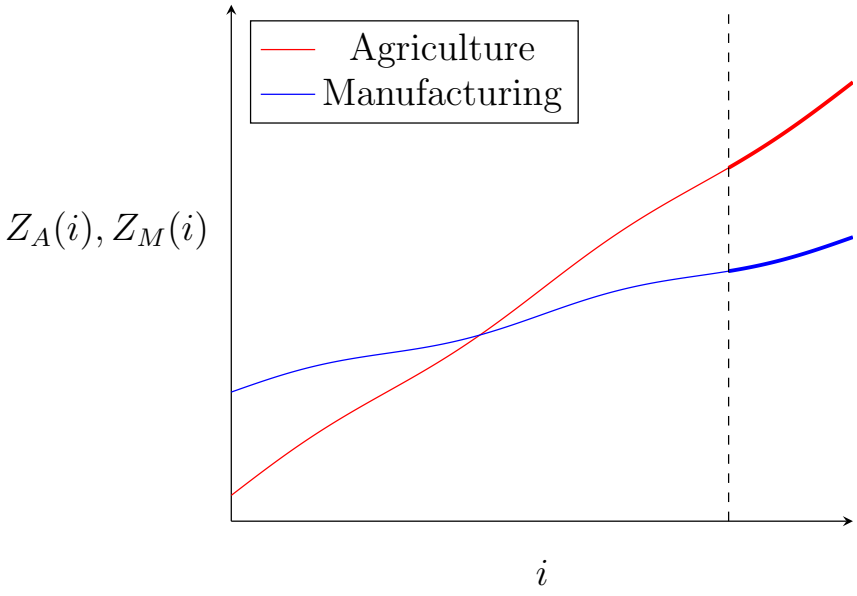
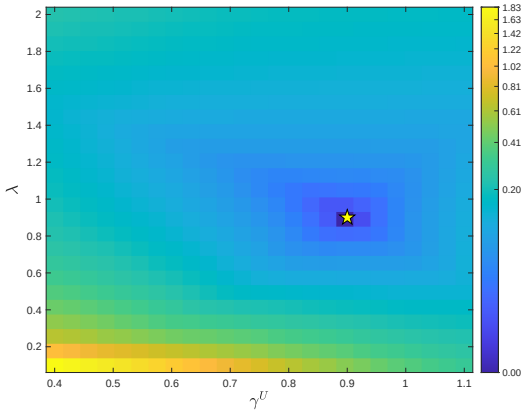
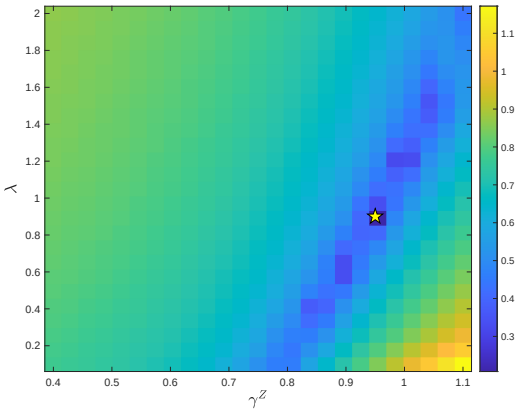


Figure H.4: Local Minimum

(a) Given $\gamma_Z$




(b) Given $\gamma_U$




(c) Given $\lambda$

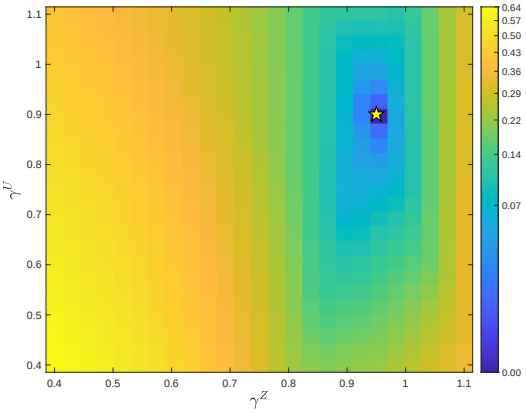
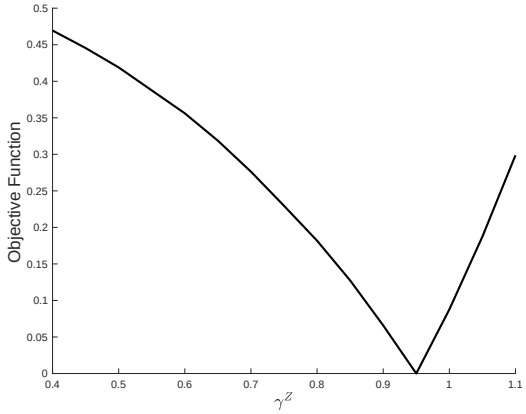
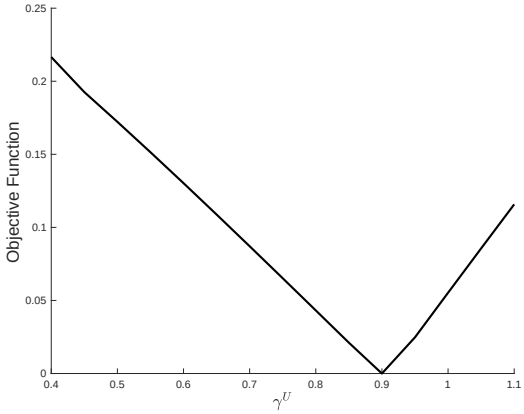


Figure H.5: Local Minimum - Parameter by Parameter

(a) $\gamma_Z$




(b) $\gamma_U$




(c) $\lambda$

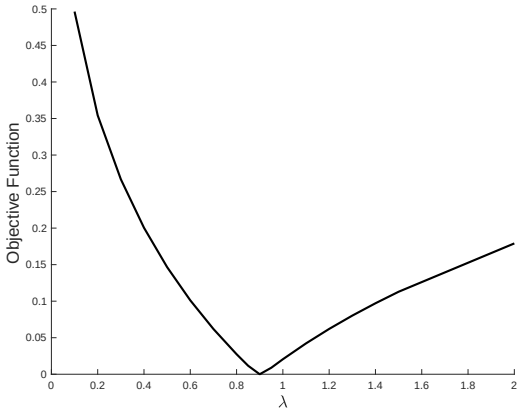


Figure H.6: Comparing Fallow with no Fallow

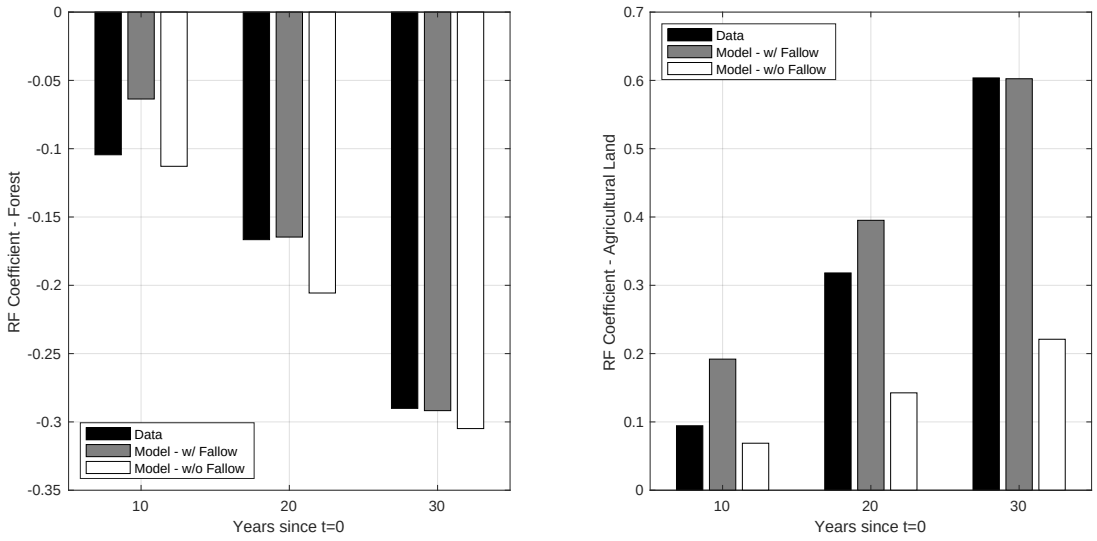



Figure H.7: Correlation between Forest Protection and $\zeta_F$

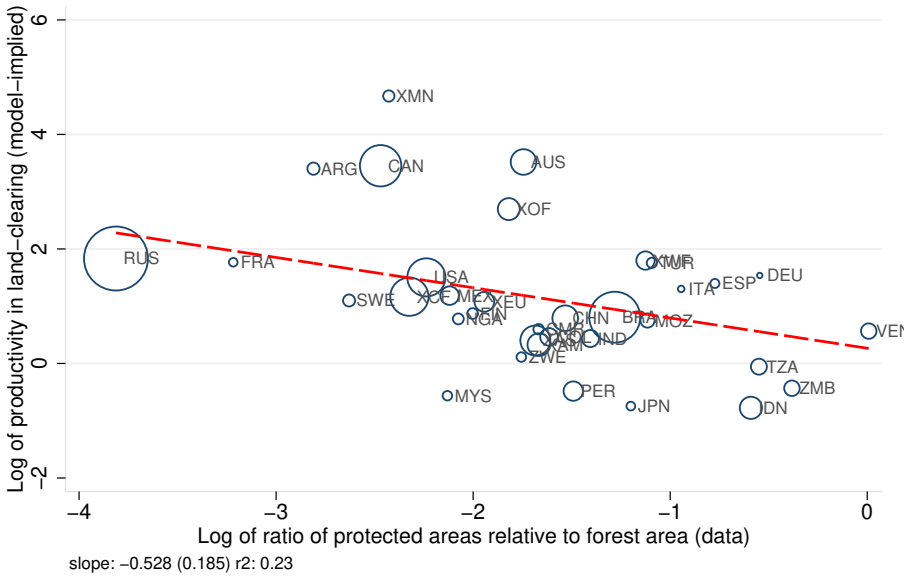


Figure H.8: Correlation between Physical Yields in the Model and in the Data

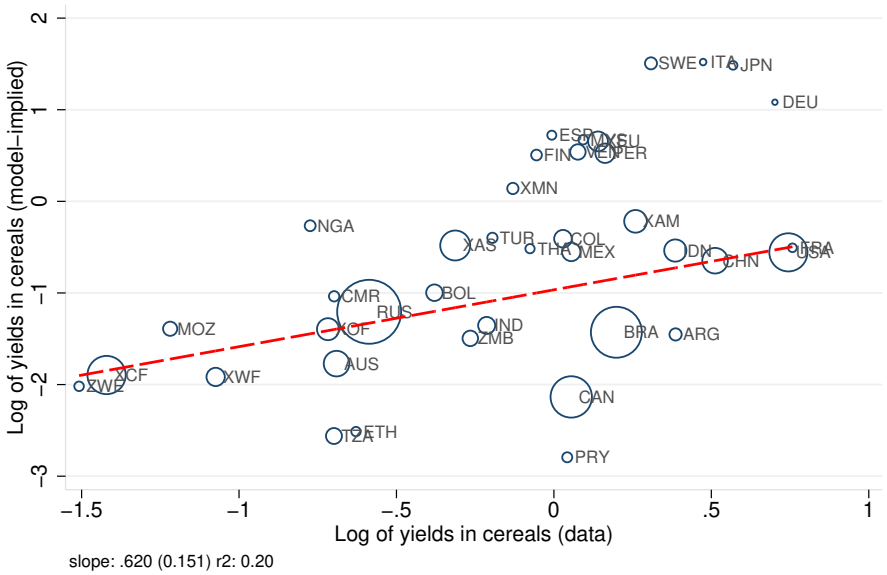



Figure H.9: Evolution of Workers

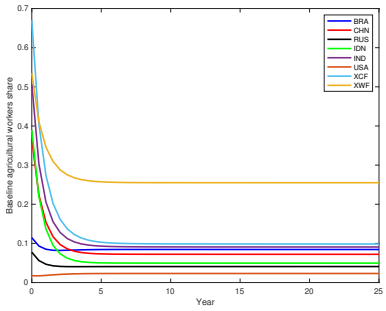



Figure H.10: Role of Persistence

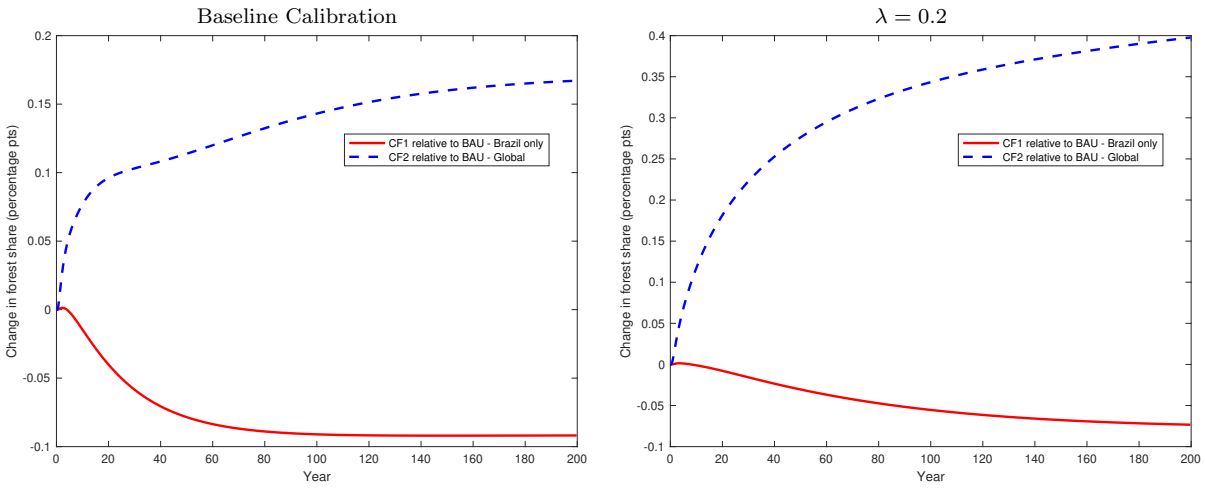
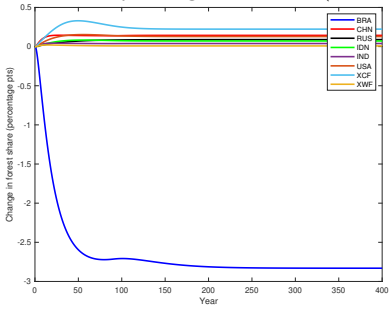


Figure H.11: Multilateral vs Unilateral Tariff Elimination: Change in Forest Area Relative to Population Growth Baseline Baseline (Global and Selected Countries)

Panel (c): Cross-country changes in forests (Counterfactual 1)




Panel (d): Cross-country changes in forests (Counterfactual 2)

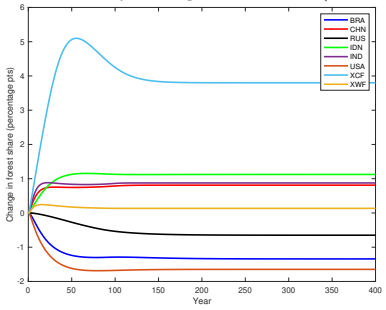
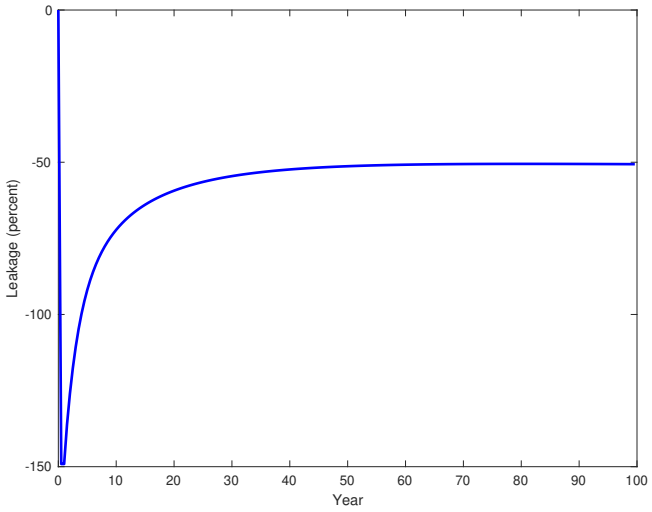



Figure H.12: Leakage from a Reduction in Import Tariff from Brazil




**Notes**: This figure shows the dynamics of the leakage from reducing tariffs for Brazil over time.

Figure H.13: Change in Forest Share versus Population

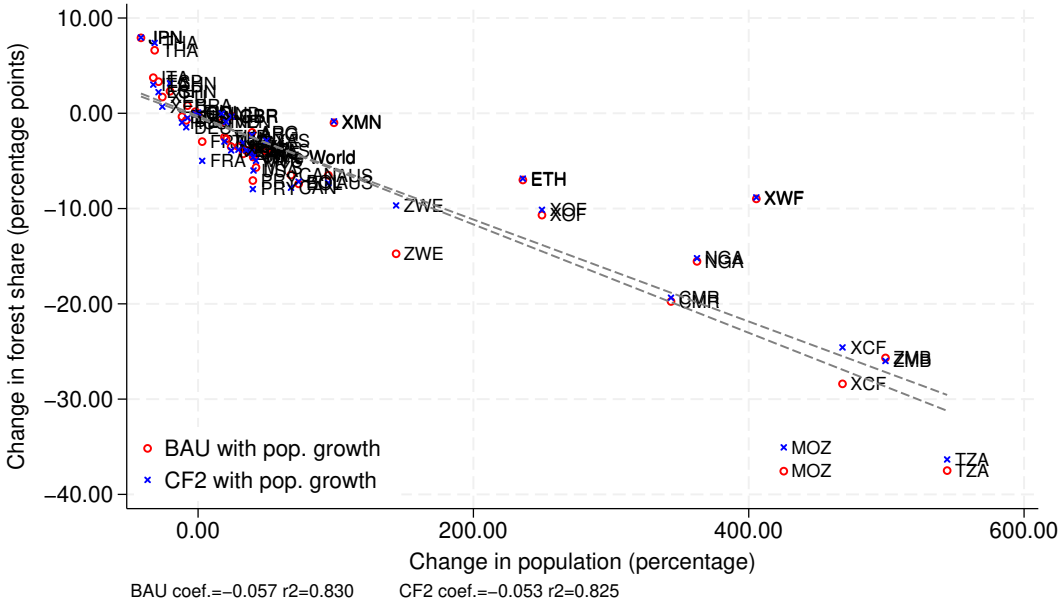


Figure H.14: Multilateral vs Unilateral Trade Cost Reduction: Change in Forest Area Relative to Baseline (Global and Selected Countries)

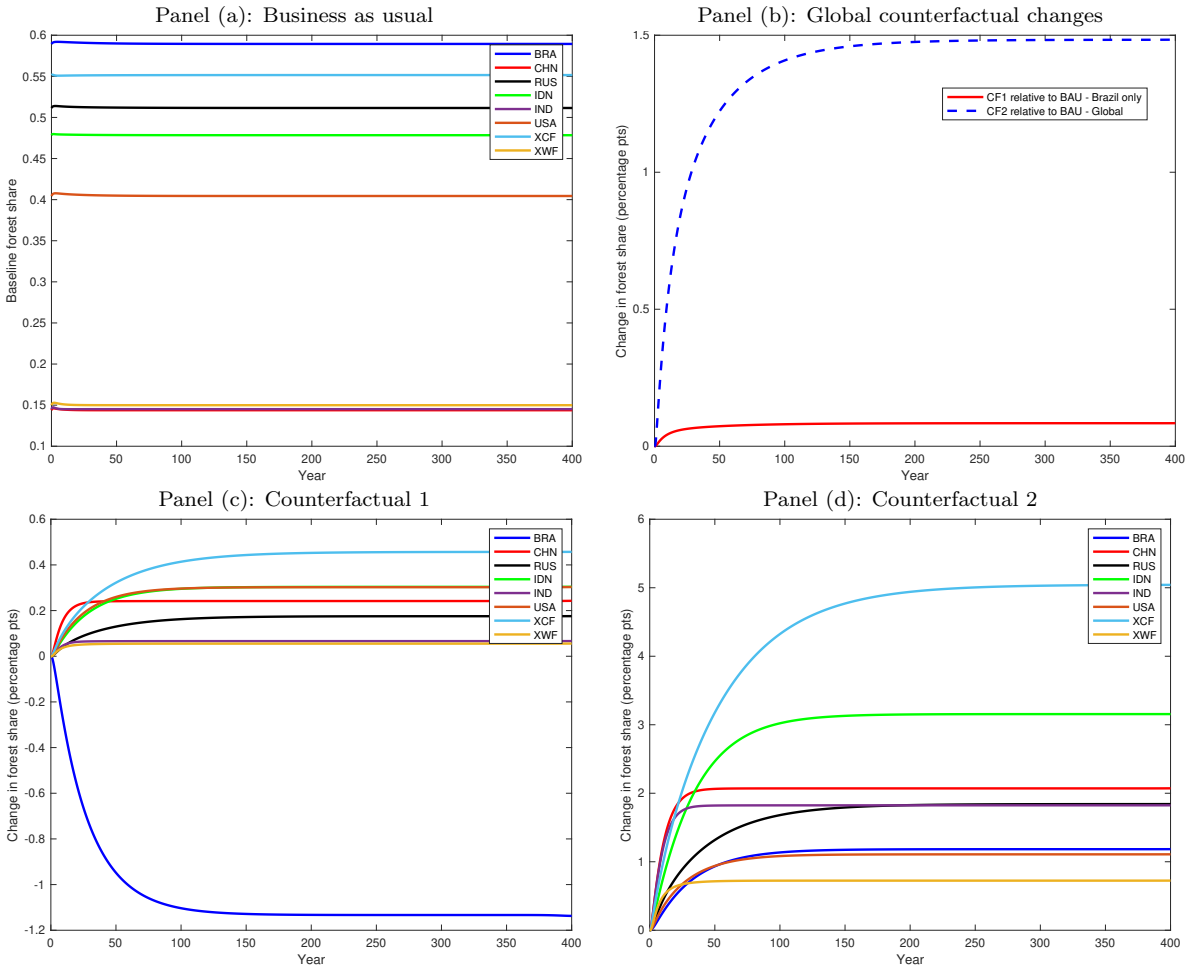
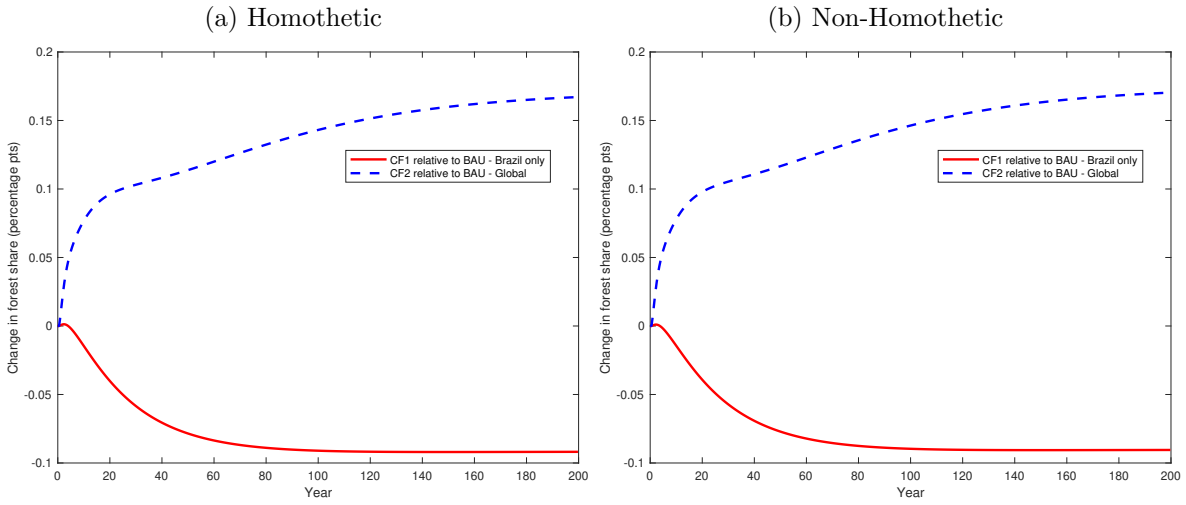


Figure H.15: Comparing Homothethic and Non-Homothetic Preferences




**Notes**: Panel (a) replicates the results from the main body of the paper. Panel (b) shows the effects when we allow for non-homothetic preferences, using the Comin et al. (2021) formulation. Specifically, we let the consumption shares depend on real income in a country, using an income elasticity parameter of 0.7 for agriculture, 1 for manufacturing, and 1.6 for services.

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