Policy Research Working Paper 10163

A Model of Amazon Deforestation, Trade and Labor Market Dynamics

Charly Porcher
Marek Hanusch

WORLD BANK GROUP
Macroeconomics, Trade and Investment Global Practice
November 2022

Policy Research Working Paper 10163

Abstract

This paper develops a dynamic spatial equlibrium model of Amazon deforestation, accounting for trade and labor markets dynamics. It uses this model to study the impact of local sectoral shocks and policies on deforestation. Conditional on the assumptions on key parameters, the analysis suggests the following: 1) an increase in external commodity demand increases deforestation; 2) agricultural productivity gains within the Amazon region likely increase deforestation (but reduce deforestation in the rest of the world) 3) manufacturing productivity in urban centers in the Amazon region decreases deforestation, especially if manufacturing firms have short rural value chains and if complemented by investments in education and training and measures to attract skills; 4) reducing transport costs increases deforestation unless it sufficiently supports higher export competitiveness of urban production; and 5) industrial policy focused on raising urban productivity, especially in sectors with short rural value chains, can reduce deforestation. The paper then discusses how policies aimed at increasing local sectoral productivity in the Amazon region could complement other measures specifically aimed at protecting the forest. Among such measures are incentivizing governments to designate undesignated public forests, enforcing forest protection laws (command and control), incentivizing afforestation, and creating alternative livelihoods for farmers in rural and urban areas.

This paper is a product of the Macroeconomics, Trade and Investment Global Practice. It is part of a larger effort by the World Bank to provide open access to its research and make a contribution to development policy discussions around the world. Policy Research Working Papers are also posted on the Web at http://www.worldbank.org/prwp. The authors may be contacted at mhanusch@worldbank.org.

Produced by the Research Support Team

A Model of Amazon Deforestation, Trade and Labor Market Dynamics

Charly Porcher[+] and Marek Hanusch[*]

JEL classification: Q15; Q24; C68

Keywords: Macroeconomics and Growth; Structural Policy and Reform; Environmental Sustainability; Green Growth; Climate Change Mitigation

[+]Georgetown University, [*]World Bank

1 Introduction

This paper studies the response of welfare and Amazon deforestation to several trends and policy scenarios in a dynamic spatial equilibrium model. This model departs from the computable general equilibrium (CGE) models often used for similar analyses (see, e.g. Ferreira-Filho and Hanusch (2022)) in three main ways. First, this model accounts for the speculation motive of deforestation by modeling the forward-looking behavior of agents. Farmers engage in deforestation when the prospect of selling the land in the medium-term is high, even if the short-term returns to agricultural activity are low. Second, this model recognizes that policies lead to selection in which farmers are able to enter, grow, and exit. Poorer farmers own less capital, less land, and are more labor intensive than richer farmers. They are also more likely to engage in deforestation if competition on the output market and demand for land increase. Third, this model allows to compare rural and urban areas within the Amazon region. Cities in the Amazon have the potential to attract rural workers and may be part of the solution to curb deforestation.

Similarly to CGE models, this model explicitly accounts for regional and international trade networks, as well as regional migration linkages. However, the description of industries is not as precise as in CGE models, and the exercises presented below are not derived from a fully calibrated model. The model is an extension of Caliendo et al. (2019) that includes endogenous land dynamics.

The paper proceeds as follows. The next section describes the deforestation process in the Amazon region, as the foundation to study the structural economic drivers of deforestation as well as policies to address them, protecting forests. Section 3 then sets up the model, describing households, production, land dynamics, and the model equilibrium. Section 4 then studies the macroeconomic, structural drivers of deforestation and section 5 lays out potential policies to counter structural deforestation pressures. The last section concludes.

2 The drivers of deforestation in the Brazilian Amazon region

Deforestation in the Amazon is linked to 1) illegal logging and 2) demand for productive land. Illegal timber extraction is linked to the value of Amazon wood, especially high value varieties like mahogany and ipê. Given attractive prices and low risk of detection and punishment, illegal timber is profitable and undercuts prices in the legal reduced impact logging industry. In principle, illegal timber extraction can happen across all types of Amazon land, public and private, often occurring alongside roads. On private land, landowners may illegally extract timber, but there is also evidence that they are victims of illegal loggers—identifying who was eventually responsible for illegal logging in private territories makes punishment difficult. In public land, illegal logging occurs in both protected and indigenous areas, in the latter putting loggers in often violent conflict with indigenous populations. These forms of illegal logging on public or private land or alongside roads happen more sporadically and are more difficult to measure. For simplicity, in the model, the only form in which illegal logging occurs is when individuals engage in deforestation of undesignated land with the prospect of creating new private agricultural land.

Demand for productive land is an important driver of deforestation. Undesignated land is a deforestation hotspot. Brazil's Forest Code allows for deforestation of up to 20% of private properties for productive land use. However, most Amazonian deforestation hotspots lie in undesignated (non-private) land (Azevedo-Ramos et al. (2020)). Deforestation on undesignated land is not legal, but it can become legal up to the 20% limit if the initially undesignated plot of land becomes regularized as private property. The process of land regularization usually involves illegal occupation of the land (Figure 1), sometimes for several years, accompanied by low productivity land use to establish a legal claim on the land. Some studies suggest

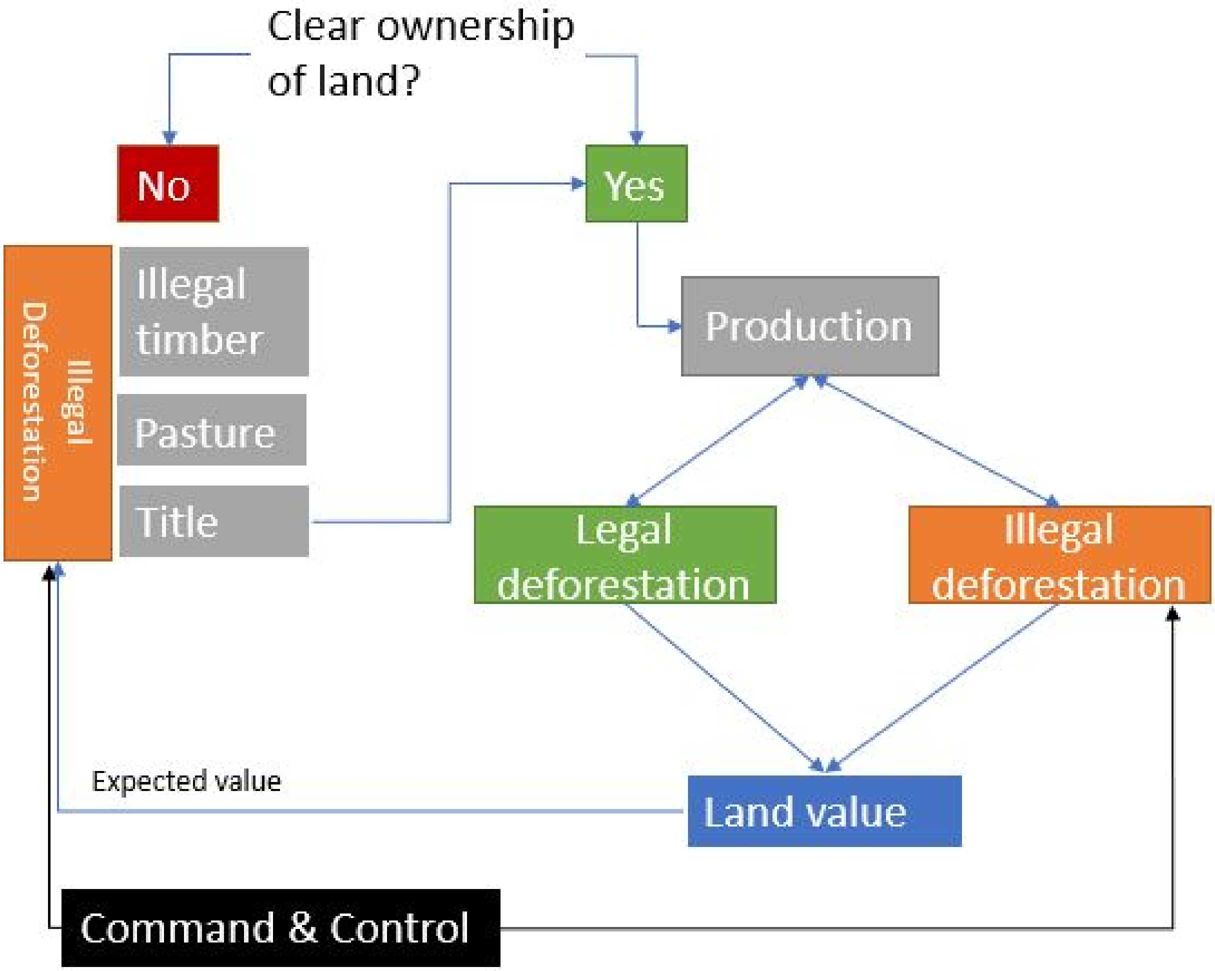


Figure 1: A conceptual framework for deforestation

that the law implicitly encourages this form of land invasion and land conversion, or land grabbing (Brito et al. (2021)).

Illegal logging and land conversion are connected. In order to make forested land suitable for productive use, especially when land has not yet been regularized, illegal extraction of prized woods can help finance a broader land clearing, often involving burning. The most common land use following deforestation is pasture and extensive (low-productivity) cattle ranching. Once the land has been in productive use for a certain period, depending by state, it can become a candidate for regularization, with legal title issued and ownership established. This motivates the assumption in the model that individuals who engage in deforestation earn income from the illegal timber they harvest, and have to wait at least one period before they can sell the newly created land for productive use.

Land prices are an important part of the deforestation story in the Amazon. Where deforestation is not simply linked to timber demand, deforestation can be largely explained by land prices. Those are determined by the demand for land and supply of land and when prices go up, deforestation can occur for two reasons: 1) the expectation of higher land prices fuels speculative motives and can increase land grabbing; 2) expanding production when land prices increase raises incentives to illegally expand into protected land. The latter may be cheaper than the alternative of intensifying production when law enforcement is weak or when input markets are imperfect (raising the cost of intensification).

3 Model

3.1 Setup

The economy consists of many regions, many sectors and many types of land use. Examples of sectors include manufacturing and non-tradable services. Examples of land uses can include cattle grazing, annual and perennial crop culture, agroforestry, and, importantly, deforestation with the purpose of extracting timber with or without the objective of creating land for another use. Regions are linked together by trade and migration networks.

More specifically, the analysis considers N locations, J sectors and S types of land use. The index n is used to identify a particular location, sectors are indexed by j, land uses by s, denote by d_s the activity consisting in deforesting native forest with the prospect of turning it into land of type s. The index k denotes an activity that could be either working in an industry, exploiting a type of land use, deforesting land to turn it into a specific type of agricultural land, or being non-employed. Therefore, there are $K = J + 2S + 1$ possible activities for a household.

In each location-industry combination, there is a competitive labor market. In each market, there is a continuum of perfectly competitive firms producing intermediate goods. Firms have a Cobb-Douglas constant-returns-to-scale technology, demanding labor, materials from all sectors and agricultural outputs from all land types. The analysis follows Eaton and Kortum (2002) and assumes that productivities are distributed Fréchet with a sector-specific productivity dispersion parameter θ_j.

Time is discrete and denoted by $t = 0, 1, 2, \ldots$. Households are forward looking, have perfect foresight, and optimally decide where to move and which activity to undertake given some initial distribution of labor across locations and activities. Households face costs to move across markets and experience an idiosyncratic shock that affects their moving decision. The following sections first characterize the dynamic problem of a household deciding where to move and which activity to undertake conditional on a path of real incomes across time and across labor markets. This is succeeded by a characteriziation of the static subproblem to solve for prices and wages conditional on the supply of labor in a given market.

3.2 Households

Households are forward looking and have Cobb-Douglas preferences over the consumption of final goods. Each period, they choose their location and activity to maximize their expected lifetime utility. Households must pay transition costs (in utils) if they choose to change their location and/or activity. They also hold idiosyncratic preferences for each location and activity. Their expected utility in any region and activity therefore takes into account their utility from consumption, minus the utility transition costs, plus their idiosyncratic preferences.

When employed as workers in a specific sector and region, they receive the local competitive market wage in that sector and region. If they engage in land use, their income is the sum of profits from sales and labor income. Since intermediate goods markets are competitive, their income from that activity is simply the wage in their activity.

Households can also earn (or spend) income from selling (or buying) land. A household who was engaged in deforestation in the previous period can sell the land they created. Conversely, households who decide to engage in land use must buy land. The local market price of land is determined so that land markets clear. Households who decide to engage in deforestation do not buy the forested land that they occupy. Instead, they pay a cost of deforestation. Part of this cost of deforestation, treated as exogenous, reflects the risk of punishment from authorities and the costs associated to formalizing land ownership. Another part becomes higher as the stock of native forest declines, reflecting the need to reach less accessible areas of the forest.

3.2.1 Preferences

In the first period ($t = 0$), a mass L_{nk0} of households is present in each location n and activity k. Households in location n and sector j each supply one unit of labor and earn a competitive market wage w_{njt}. Households engaged in the type of land use s receive income y_{nst}, described below. Households who decide to engage in deforestation d_s produce lumber and receive income y_{nlt}. Given their income, households choose how to allocate consumption over local sectoral and agricultural goods with a Cobb-Douglas aggregator. There are $G = J + S + 1$ final goods, consisting in J industrial goods, S agricultural products and lumber produced by people engaging in deforestation, that is indexed by G. Preferences of households in location n and activity k, $U(C_{nkt})$, are expressed as

$$C_{nkt} = \prod_{g=1}^{G} (c_{nkgt})^{\alpha_g}$$

where c_{nkgt} is the consumption of goods g in market nk at time t and α_g is the final consumption share , with $\sum_{g=1}^{G} \alpha_g = 1$.[1]

Non-employment is represented by sector zero in each region. Non-employed households consume $C_{n0t} = b_n$ from home production.

3.2.2 Household Problem

Households are forward-looking. They discount the future at rate $\delta \geq 0$. Migration decisions are dynamic. They are subject to transition costs between locations and activities. Land use dynamics are made explicit by the existence of land conversion costs between each type of land use. For example, the direct conversion of native forest to crop culture is difficult because the recently deforested land is not suitable for crops. This will be captured by a high cost of converting native forest into crops. These different obstacles to the free transition of households between locations and activities are represented by the costs $\tau_{nkn'k't}$ that depend on the origin (nk) and destination ($n'k'$). These costs are additive and measured in terms of utility. In particular, in the case where households have engaged in deforestation with the purpose of turning forest into some specific land type, the transition to this land type is free. Hence, for any land use activity $k \in \{J+1, \ldots, J+S\}$ and the associated deforestation activity $k' = k + S$, $\tau_{nk'nkt} = 0$.

In addition, households draw idiosyncratic shocks for each location and activity. Denote by ϵ_{inkt}, $n = 1, \ldots, N$, $k \in \{1, \ldots, K\}$ the preference shock of household i in period t for performing activity k in location n.

Households first observe the prevailing wages and prices in all markets and the realizations of their idiosyncratic shocks. Households who begin the period t in a labor market nk, can choose to relocate before engaging in their activity and earning an income.

The value of starting period t in location n and activity k is

$$v_{nkt}(\epsilon_{it}) = \max_{n',k'} \left\{ U\left(\left(y_{n'k't} + \rho_{nkn'k't} \right) / P_{n't} \right) - \tau_{nkn'k't} - d_{n'k't} + \epsilon_{in'k't} + \delta V_{n'k't+1} \right\},$$

where $V_{n'k't+1} \equiv \mathbb{E}\left[v_{n'k't+1}(\epsilon_{it+1}) \right]$ with the expectation taken over future realizations of the idiosyncratic shock, $y_{n'k't}$ is the return from performing each activity, i.e. the labor

---

[1] In an extension of the model, this analysis assumes that households have nested CES preferences over the consumption of final goods. Two nests are of particular interest to recognize the higher substitutability between some goods. One nest contains agricultural products from high-productive and low-productive farmers. The second contains timber from legal concessions and timber from illegal deforestation. The higher substitutability between these goods implies higher competitive pressure between the activities within a nest.

income for salary workers, the profit from selling the agricultural product for each of the land uses, the profit from selling lumber products if the household engages in deforestation, or home production. As described below, households who engage in land use provide one unit of labor and produce intermediate land goods in perfectly competitive markets. Their income is therefore the sum of profits from sales and labor income. Since profits are zero, their income is simply the wage in their activity. All deforestation activities $k, \in \{J+S+1, \ldots, J+2S\}$ produce the same output, lumber, and therefore offer the same income $w_{n'Gt}$.

$$y_{n'k't} = \begin{cases} w_{n'k't} & \text{if } k' \in \{1, \ldots, J+S\} \\ w_{n'Gt} & \text{if } k' \in \{J+S+1, \ldots, J+2S\} \\ b_{n'} & \text{if } k' = K \end{cases},$$

The net returns from land $\rho_{nkn'k't}$ are the difference between the household's payoff from selling the land they owned in the origin location and activity nk (if any) and buying the land in the new location and activity $n'k'$:

$$\rho_{nkn'k't} = \mathbb{1}_{\{k \in \{J+1,\ldots,J+2S\}\}} r_{nkt} - \mathbb{1}_{\{k' \in \{J+1,\ldots,J+S\}\}} r_{n'k't}$$

A household who was engaged in deforestation and decides to move to another location can sell the land they created. Formally, for any land use activity $k \in \{J+1, \ldots, J+S\}$ and the associated deforestation activity $k' = k+S$, $r_{nkt} = r_{nk't}$. Households who decide to engage in deforestation do not buy the land that they occupy from the native forest. Instead, they pay a cost of deforestation that becomes higher as the stock of native forest declines,

$$d_{n'k't} = \frac{d}{F_{n't}} \mathbb{1}_{\{k' \in \{J+S+1,\ldots,J+2S\}\}}.$$

The idiosyncratic shocks ϵ_{it} are independent across time periods and workers. For every worker i and period t, the variables in the set ϵ_{it} follow a Generalized Extreme Value distribution with cumulative distribution function

$$F(\epsilon_{it}) = \exp\left(-\sum_{n=1}^{N} \left(\sum_{k=1}^{K} \exp\left(-\epsilon_{inkt}/\lambda\right) \right)^{\lambda} \right), \qquad \text{with } 0 < \lambda \leq 1.$$

This distribution assumes that the idiosyncratic shocks ϵ_{inkt} are independent of each other when they correspond to different locations, but they may be correlated across activities within a single location.[2]

Using the properties of the Generalized Extreme Value distribution, the following is obtained

$$V_{nkt} = \ln\left(\sum_{n'}^{N} \exp\left(\lambda IV_{nkn't}\right) \right), \qquad IV_{nkn't} = \ln\left(\sum_{k'}^{K} u_{nkn'k't}^{1/\lambda} \right), \tag{1}$$

defining $u_{nkn'k't} \equiv \exp\left(U((y_{n'k't} + \rho_{nkn'k't})/P_{n't}) - \tau_{nkn'k't} - d_{n'k't} + \delta V_{n'k't+1}\right)$. This equation illustrates that the value of being in market nk depends on the value of reaching any other market $n'k'$ from nk.

3.2.3 Mobility Decisions

Denote by $\mu_{nkn'k't}$ the share of households that migrate from market nk to $n'k'$, then

---

[2] The within-location cross-activity correlation in ϵ_{inkt} depends on the value of λ; it decreases as λ increases, becoming equal to zero when $\lambda = 1$.

$$\mu_{nkn'k't} = \frac{u_{nkn'k't}^{1/\lambda} \exp\left(IV_{nkn't}\right)^{\lambda-1}}{\sum_{n''=1}^{N} \exp\left(IV_{nkn''t}\right)^{\lambda}}. \tag{2}$$

Hence, markets offering a higher utility through better access to other markets are the ones that tend to attract more migrants. The distribution of labor across markets evolves over time as

$$L_{n'k't+1} = \sum_{n=1}^{N}\sum_{k=1}^{K} \mu_{nkn'k't+1} L_{nkt}. \tag{3}$$

This condition describes the evolution of the distribution of the workforce across markets. Once the supply of workers in each market is determined, a static production environment is defined that will establish equilibrium wages and land prices at each time t.

3.3 Production

Firms in each sector, as well as households engaged in production on the land they occupy, produce many varieties of intermediate goods. The technology to produce these intermediate goods may require labor, land (specific to each sector), and final goods as inputs. Trade costs are of the "iceberg" type. One unit of any variety of good shipped from one region to another requires producing more than one unit in the origin. Intermediate goods demanded for the production of any given good and from all regions are aggregated into a local final good that can be thought as a bundle of goods purchased from different regions.

3.3.1 Intermediate Goods

Firms in sector $g = \{1, \ldots, J\}$ and households who produce on the land they occupy, $g = \{J+1, \ldots, S+1\}$, in region n, are able to produce many varieties of intermediate goods. Intermediate goods' total factor productivity comprises a component A_{ngt} that varies over time and across sectors and locations and is common to all varieties in a market, and a component z_{ng} that is specific to each variety.

A producer of an intermediate variety with efficiency z_{ng} delivers output with constant returns to scale:

$$q_{ngt} = z_{ng}\left(A_{ngt} l_{ngt}\right)^{\gamma_{ng}} \prod_{g'=1}^{G} M_{ngg't}^{\gamma_{ngg'}},$$

where l_{ngt} is the labor input and $M_{ngg't}$ the material input from good g' demanded in the production of good g and region n to produce q units of an intermediate variety with efficiency z_{ng}. The parameter $\gamma_{ng} \geq 0$ is the fraction of value added in the production of good g and region n, and $\gamma_{ngg'} \geq 0$ is the fraction of materials from good g' that are used to produce good g and region n. The price of an input bundle is

$$x_{ngt} = B_{ng} w_{ngt}^{\gamma_{ng}} \prod_{g'=1}^{G} P_{ng't}^{\gamma_{ngg'}}, \tag{4}$$

where B_{ng} is a constant and P_{ngt} is the price index of goods purchased from sector g for final consumption in region n. The unit cost of intermediate goods with efficiency z_{ng} is then $x_{ngt}/\left(z_{ng}A_{ngt}^{\gamma_{ng}}\right)$.

Barriers to regional trade are represented by iceberg trade costs $\kappa_{n'ngt}$.[3]

---

[3] Note in terms of notation that, contrary to the description of migration flows where the the subscripts were ordered by origin first, destination second, the trade flows are described by putting the destination subscript

The price of a specific variety in a given destination location n' is equal to the smallest unit cost across possible origin locations, net of trade costs. Hence, for any vector of productivity draws across locations $z_g = (z_{1g}, \ldots, z_{Ng})$,

$$p_{n'gt}(z_g) = \min_n \left\{ \frac{\kappa_{n'ngt} x_{ngt}}{z_{ng} A_{ngt}^{\gamma_{ng}}} \right\}.$$

3.3.2 Local Land and Industrial Aggregate Goods

The varieties of intermediate goods each industrial or land sector g are aggregated into a local final good denoted by Q. This final good is comprised of a bundle of goods purchased from different regions. Denote by Q_{ngt} the amount of aggregate good g produced (either an industrial or land good) in location n, and let $q_{ngt}(z_g)$ be the quantity demanded of an intermediate good of variety z_g. The output of local industrial and land goods is produced under perfect competition and is given by

$$Q_{ngt} = \left(\int_{z_g} q_{ngt}(z_g)^{1-1/\eta_{ng}} d\phi_g(z_g) \right)^{\eta_{ng}/(\eta_{ng}-1)},$$

where the integral is over $z_g \in \mathbb{R}_+^N$, with the joint distribution $\phi_g(z_g) = \exp\left(\sum_{n=1}^N z_{ng}^{-\theta_g}\right)$ over the vector z_g.

These local land and industrial aggregate goods are used for final consumption, but are also themselves used as material inputs for the production of intermediate varieties.

The price of the aggregate land or industrial good g in region n' at time t, along with the local price index $P_{n't}$, relevant for consumers, are given by

$$P_{n'gt} = \Gamma_{n'g} \left(\sum_{n=1}^N (x_{ngt}\kappa_{n'ngt})^{-\theta_g} A_{ngt}^{\theta_g \gamma_{ng}} \right)^{-1/\theta_g}, \qquad P_{n't} = \prod_{g=1}^G P_{n'gt}^{\alpha_g}. \tag{5}$$

where the properties were used of the Fréchet distribution, and Γ_{ng} is a constant.[4]

The share of total expenditure in market $n'g$ on goods g from market n, $\pi_{n'ngt}$ is given by

$$\pi_{n'ngt} = \frac{(x_{ngt}\kappa_{n'ngt})^{-\theta_g} A_{ngt}^{\theta_g \gamma_{ng}}}{\sum_{n''=1}^N (x_{n''gt}\kappa_{n'n''gt})^{-\theta_g} A_{n''gt}^{\theta_g \gamma_{n''g}}}. \tag{6}$$

3.3.3 Market Clearing

X_{ngt} denotes the expenditure on good g in region n. The goods market clearing implies

$$\begin{aligned} X_{ngt} &= \sum_{g'=1}^G \gamma_{ng'g} \underbrace{\sum_{n'=1}^N \pi_{n'ng't} X_{n'g't}}_{(g')\text{'s income in } n} \\ &\quad + \alpha_g \Bigg(\underbrace{\sum_{k=1}^K y_{nkt} L_{nkt}}_{\text{labor income}} + \underbrace{\sum_{n'=1}^N \sum_{k,k'=1}^K \rho_{n'k'nkt} L_{n'k't-1} \mu_{n'k'nkt}}_{\text{net rent income}} \Bigg). \end{aligned} \tag{7}$$

---

first. This is motivated by the fact that migration shares represent gross flows of people relative to the total *origin* population, while trade shares represent the value of flows of goods relative to the total expenditures of the *destination* market.

[4] This expression is obtained under the assumption that $1 + \theta_g > \eta_{ng}$.

The first sum represents the value of the total demand for good g produced in location n in the form of material inputs to the production of all goods in all locations. The second term is the value of the final consumer demand in region n.

The labor market clearing in location n' for good g implies

$$w_{ngt}L_{ngt} = \gamma_{ng} \sum_{n'=1}^{N} \pi_{n'ngt} X_{n'gt}, \tag{8}$$

where the left hand side is the total payment received by workers engaged in the production of good g in location n, the right hand side is the expenditure on labor in the production of good g.

In every location n, at the beginning of each period, all households previously engaged in an activity involving land use, i.e. $k \in \{J+1, \ldots, J+2S\}$, who decide to move to another location, sell their plot of land at price r_{nkt}. Conversely, all households moving to another location n' and who choose a land activity have to buy a plot of land at price $r_{n'kt}$.

The total number of plots of type s that are for sale at the beginning of period equals the mass of households previously in activity s, or deforesting to create land of type s, who decide to move to another location. The total number of plots demanded equals the mass of households moving to activity s from another location. Hence, land prices are solution to

$$L_{nst-1} + L_{nd_st-1} = L_{n'st}, \qquad \forall s = \{1, \ldots, S\}, \tag{9}$$

where $d_s = s + S$.

3.4 Land Dynamics

All locations have the same area, equal to 1. Denote by F_{nt} the share of each location that is covered by native forest. Each period, the naturally forested area decreases by the mass of people engaging in deforesting,[5] i.e.,

$$F_{nt+1} = \max\{0, F_{nt} - \sum_{s=J+1}^{J+S} \psi_{nd_s} L_{nd_st}\},$$

where ψ_{nd_s} is the area that can be cleared by one household during one period and L_{nd_st} is the mass of households engaging in deforestation in period t.

Each household engaged in land use activity s in location n exploits an area ψ_{ns}. Therefore, the local land constraint is written as

$$\sum_{s=J+1}^{J+2S} \psi_{ns} L_{nst} + F_{nt} = 1.$$

3.5 Equilibrium

The distribution of the workforce and land use across all markets (L_t, F_t) constitute the endogenous state of the economy. The time-varying fundamentals are the sectoral-regional productivities $A_t = \{A_{nkt}\}_{k=1,N=1}^{S,N}$, trade costs $\kappa_t = \{\kappa_{n'njt}\}$ and costs to labor relocation $\tau_t = \{\tau_{nkn'k't}\}$. The constant fundamentals are the home production across regions $b = \{b_n\}$. The time-varying fundamentals is denoted by $\Theta_t \equiv (A_t, \kappa_t, \tau_t)$ and constant fundamentals by $\bar{\Theta} \equiv (b)$. The parameters in the model, assumed constant throughout the paper, are given

---

[5] In one extension of the model, the analysis considers an intermediary state of the land: each period, some fraction of the agricultural land turns into *degraded* agricultural land at a constant rate, a state that is neither suitable for agricultural production nor primary forest. This degraded land itself returns into primary forest at some (slow) constant rate.

by the value added shares (γ_{ng}); the input-output coefficients ($\gamma_{ngg'}$); the final consumption expenditure shares (α_g); the discount factor (δ); the trade elasticities (θ_g); and the migration elasticity (λ).

The next step is to find equilibrium wages $w_t = \{w_{ngt}\}$ and the equilibrium allocations $\pi_t = \{\pi_{nn'gt}\}, X_t = \{X_{ngt}\}$, given $(L_t, \Theta_t, \bar{\Theta})$ and the sequence of land rents $\{r_{nst}\}$. This equilibrium can be referred to as a temporary equilibrium.

Definition 1. *Given* $(r_t, L_t, \Theta_t, \bar{\Theta})$*, a temporary equilibrium is a vector of wages* $w(r_t, L_t, \Theta_t, \bar{\Theta})$ *that satisfies the equilibrium conditions of the static subproblem,* (4) *to* (8)*.*

The temporary equilibrium of the model is the solution to a static multi-location interregional trade model. Suppose that, for any $(r_t, L_t, \Theta_t, \bar{\Theta})$, one can solve the temporary equilibrium. Then the wage rate can be expressed as $w_t = w(r_t, L_t, \Theta_t, \bar{\Theta})$, and given that goods prices are all functions of wages, one can express real wages as $\omega_{nkn'k'}(r_t, L_t, \Theta_t, \bar{\Theta}) = (y_{n'k't} + \rho_{nkn'k't})/P_{nt}$. After defining the temporary equilibrium, one can now define the sequential competitive equilibrium of the model given a path of exogenous fundamentals $\{\Theta_t\}_{t=0}^{\infty}$ and given $\bar{\Theta}$. Let $\mu_t = \{\mu_{nkn'k't}\}$ and $V_t = \{V_{nkt}\}$ be the migration shares and lifetime utilities, respectively. The definition of a sequential competitive equilibrium is given as follows.

Definition 2. *Given* $(L_0, \{\Theta_t\}_{t=0}^{\infty}, \bar{\Theta})$*, a sequential competitive equilibrium is a sequence of* $\{r_t, L_t, \mu_t, V_t, w(r_t, L_t, \Theta_t, \bar{\Theta})\}_{t=0}^{\infty}$ *that solves equilibrium conditions* (1) *to* (3)*,* (9) *and the temporary equilibrium at each* t*.*

In Appendix A, the set of equations is specified that solves for the sequential competitive equilibrium in time differences. Appendix B describes a solution algorithm.

4 The Role of Global Demand and Local Sectoral Shocks in Deforestation

This section evaluates the predictions of the model for welfare and deforestation in response to global demand and local productivity shocks. It relies on the baseline model or on simple extensions, using illustrative values for the set of parameters.

4.1 External demand

The predictions of the model for welfare and deforestation are evaluated in response to global demand and local productivity shocks. The analysis relies on the baseline model or on simple extensions, using illustrative values for the set of parameters. External commodity demand is a major driver of deforestation. Demand for Amazon wood can raise illegal large-scale deforestation as sustainable practices of individually extracting prized species are relatively expensive, resulting instead in highly invasive timber harvesting.[6] External demand for agricultural goods will increase demand for land and given the high land-intensity of the sector it will have the strongest impact on raising land prices, thus encouraging deforestation where property rights and law enforcement are weakest.

---

[6] Although not included in this analysis, rising minerals prices (such as gold) also drives deforestation. Mining (legal and illegal wildcat mining by so-called garimpeiros) is associated with more deforestation. It requires road connections, resulting in illegal logging across the roads. It also attracts populations that will be supplied by local agricultural activity, raising local demand for land. Sonter et al. (2017) find that mines in the Amazon increase deforestation within a perimeter of about 70km, largely due to expanded permanent cropland and logging for fuelwood, accounting for about 10% of Amazon direct and indirect deforestation between 2005 and 2015.

4.2 Agricultural productivity

Agricultural productivity growth can come from two effects: 1) factor reallocation (e.g. due to greater market integration), 2) technology adoption. Both are likely to increase deforestation.

4.2.1 Market integration

Increased integration of the Amazonian agriculture sector into global markets may lead to an increase in deforestation through selective exit of small farmers. To illustrate this channel, the model described in the previous section is extended to account for two types of farmers, imperfectly competing on agricultural markets:

- **Productive farmers**: high total factor productivity and land intensive (they use more units of land per unit of output than the unproductive farmers).
- **Unproductive farmers**: low total factor productivity and labor intensive. They face very high trade costs so very few of them export.

Productive farmers expand in response to trade liberalization. In the first period, the trade costs of agricultural goods produced by the productive farmers decline by half and remain at this lower value forever. The trade costs for unproductive farmers remains at its initial level, to capture the fact that they are unlikely to be able to take advantage of a trade liberalization, as one would expect in the presence of high fixed costs of becoming an exporter.

Productive farmers use more land per unit of output. As trade costs decline, productive farmers seize opportunities from global markets, expand market share, use more land, implicitly consolidating the land of unproductive farmers. Despite having a higher total factor productivity, productive farmers are particularly land-intensive and require more units of land per unit of output. Hence, their expansion leads to an increase in deforestation. The reallocation of production towards productive farmers also leads to a rise aggregate productivity in agriculture. This in turns leads to higher demand for Amazon's agricultural products from the rest of the world, further increasing deforestation. This channel is described in the next exercise.

Unproductive farmers exit and turn to deforestation. Unproductive farmers compete with productive farmers on the factor markets for land and labor as well as on the product market for agricultural output. As the productive farmers expand, the most attractive option for unproductive farmers is to exit agricultural production and turn to deforestation to benefit from the high price of land. Another consequence of the increase in deforestation is the increase in supply of illegal timber, which drives down the price of timber (legal and illegal).

4.2.2 Technology adoption in agriculture

A rise in agricultural productivity in the Amazon is likely to lead to an increase in deforestation. To illustrate the channels through which an improvement in agricultural technology in the Amazon can increase deforestation, it helps to consider a simple version of the model described in the previous section. There are two regions, the "Amazon" and the "rest of the world". There are three possible activities: manufacturing, agriculture, and deforestation. As described above, people who choose deforestation as their activity produce timber during one period, and create a parcel of land that they can sell next period to people willing to engage in agriculture.

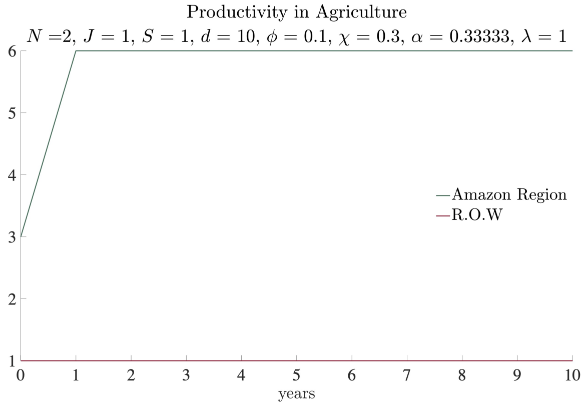
Initially, the economy is in a steady state. This steady state features gross migration and trade flows each period, such that absent any change in productivities, trade or migration costs, employment and prices would remain constant over time. In the first period, the productivity in agriculture is unexpectedly multiplied by two in the Amazon (only), and remains at this higher level forever. Figure 2 illustrates the persistent productivity shock in agriculture in the Amazon occurring in the first period. The figures below describe the transition of the economy to the new steady state with higher agricultural productivity in the Amazon.

Productivity growth benefits all workers in the Amazon. Figure 3 illustrates the welfare effects of the agricultural productivity shock in the Amazon, as well as the effects on deforestation. Expectedly, welfare in agriculture rises in the Amazon, in large part thanks to the higher wages offered in that activity (see Figure 4). The welfare in manufacturing and timber sector also increases, due to lower prices of all goods (cheap agricultural products make cheap inputs all goods and lead to a global decline in prices), and the prospect of higher wages in agriculture (see Figure 5).

Deforestation in the rest of the world decreases. However, agricultural workers are worse off in the rest of the world, as a result of the competition from agricultural producers in the Amazon (see the wage effects in Figure 4). Manufacturing workers in the rest of the world do not suffer from the improved competitiveness of Amazon's agriculture, they experience welfare gains due to lower prices and a moderate wage loss that is mitigated by the out-migration of manufacturing workers to the Amazon. Workers engaging in deforestation in the rest of the world are also slightly worse off, as a result of the decline in wages in that sector and the price of land (both due to a lower demand for the rest of the world's agricultural products).

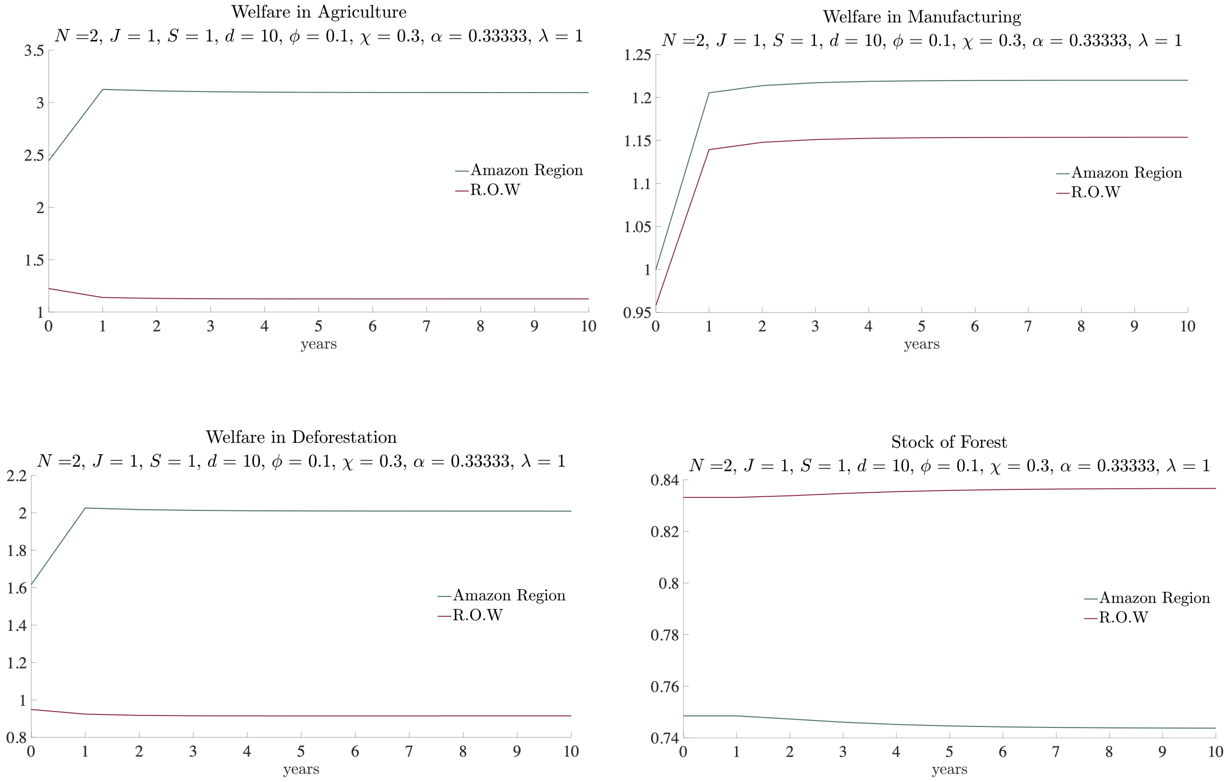
The increase in foreign demand likely dominates the benefit of land intensification. The increase in agricultural productivity in the Amazon leads to a slight increase in deforestation in the Amazon, and a decrease in deforestation in the rest of the world. The increase in deforestation in the Amazon is the net effect of two counter-acting mechanisms. First, the higher productivity of agriculture in the Amazon allows to serve the total demand with a lower total use of land. Second, the higher productivity leads to a large increase in exports to the rest of the world. For reasonable values of the trade elasticity (i.e., large enough), the increase in exports is sufficiently large to lead to an overall increase in the demand for land in the Amazon. This rise in demand for agricultural goods from the Amazon is particularly strong—with a large increase in deforestation—if agricultural production can expand easily by attracting workers, i.e. if the migration elasticity is large (see Figure 4). Finally, the increase in agricultural productivity in the Amazon may lead to a decline in deforestation if it is combined with a global ban on the purchase by foreign consumers of products linked to deforestation.

Figure 2: Exogenous Rise in Productivity in Agriculture in the Amazon



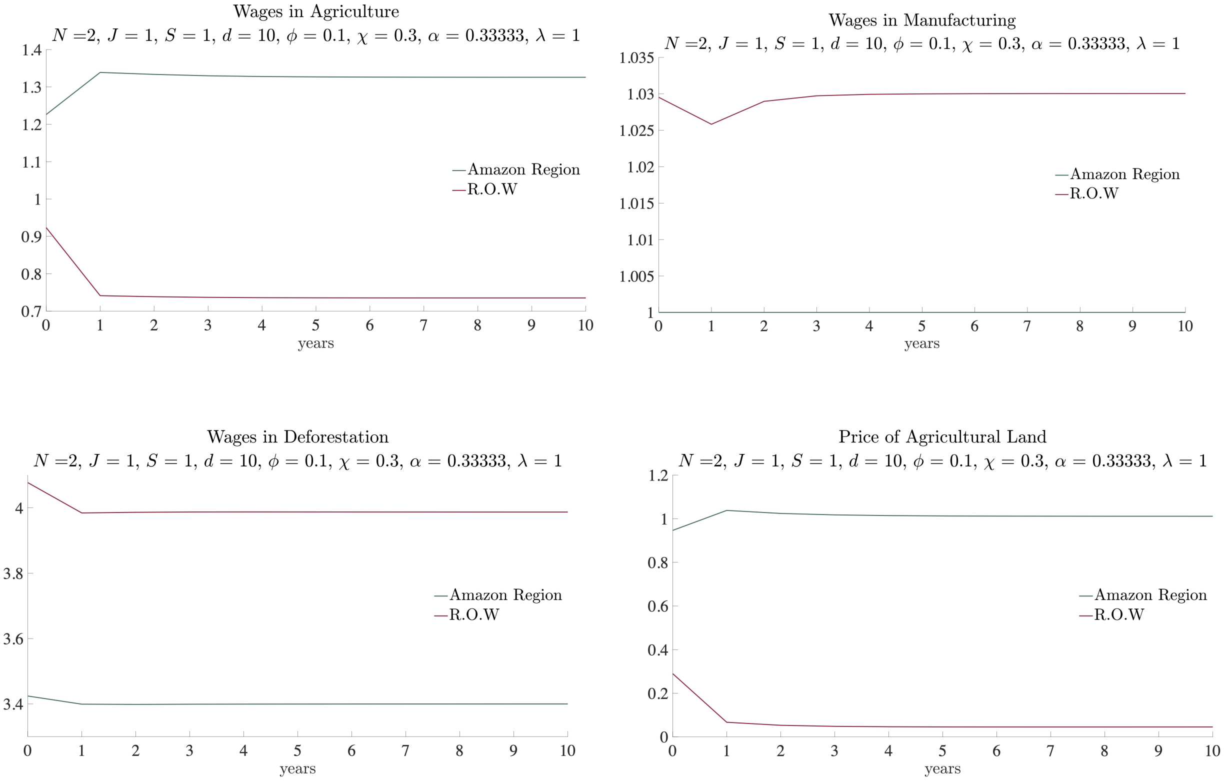
Note: In this example, productivity in agriculture in the Amazon was already three times higher in the Amazon than in the rest of the world in the initial steady state. This assumption is the only difference between the two regions in the initial steady state is purely for illustrative purposes. The parameters of the model are chosen for illustrative purposes and are not calibrated on data. The discount factor is $\delta = 0.96$; the share of consumer expenditures on each of the three goods g is $\alpha_g = 1/3$; the degree of independence in taste shocks for activities within a location is $\lambda = 1$ ($\lambda = 1$ means independence); trade elasticities for all goods g are set to $\theta_g = 1$; the weight of labor expenditure in the production intermediate goods g is set in all regions n to $\gamma_{ng} = 0.8$; the concavity of the deforestation cost is set to $\phi = 0.1$; the fraction of cleared land that returns to forest each period is $\chi = 0.3$.

Figure 3: Welfare and Deforestation Effects of A Rise in Productivity in Agriculture in the Amazon



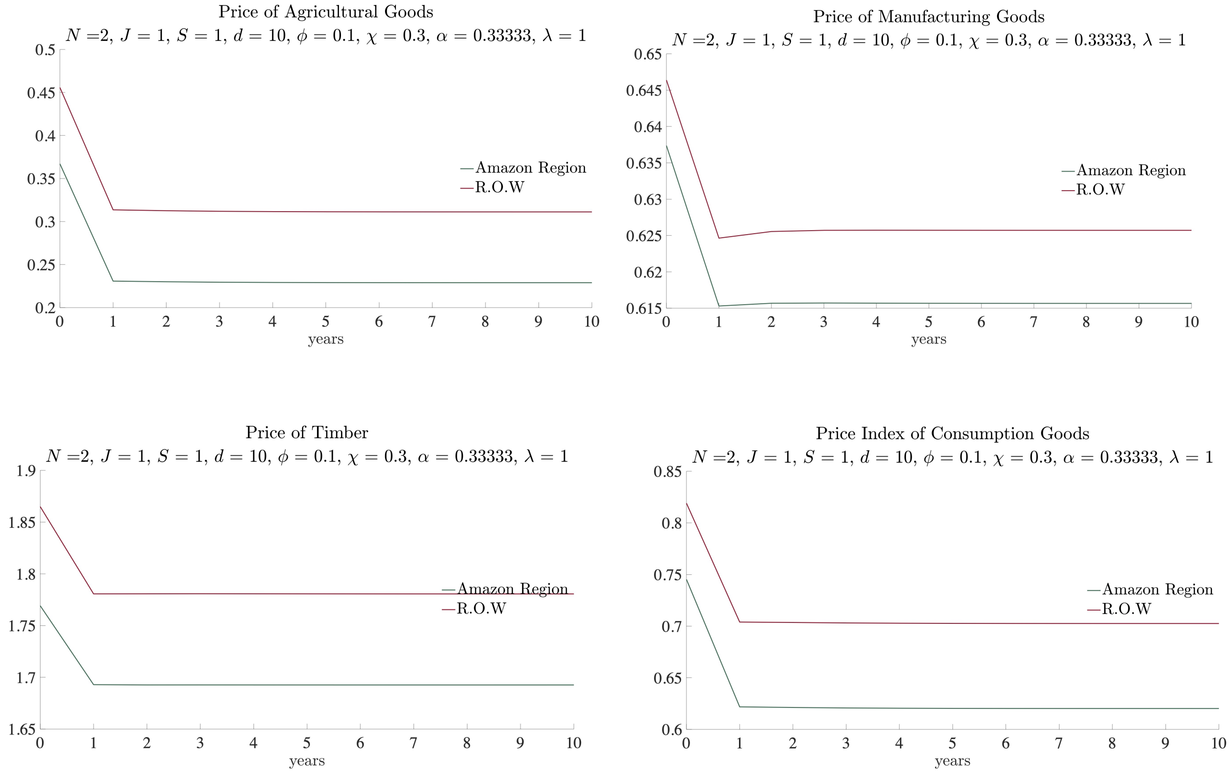
Note: Welfare measures in all regions and activities are normalized by the welfare in manufacturing in the Amazon in the initial period (steady state). The parameters of the model are chosen for illustrative purposes and are not calibrated on data. The discount factor is $\delta = 0.96$; the share of consumer expenditures on each of the three goods g is $\alpha_g = 1/3$; the degree of independence in taste shocks for activities within a location is $\lambda = 1$ ($\lambda = 1$ means independence); trade elasticities for all goods g are set to $\theta_g = 1$; the weight of labor expenditure in the production intermediate goods g is set in all regions n to $\gamma_{ng} = 0.8$; the concavity of the deforestation cost is set to $\phi = 0.1$; the fraction of cleared land that returns to forest each period is $\chi = 0.3$.

Figure 4: Wages and Land Price Effects of A Rise in Productivity in Agriculture in the Amazon



Note: The wage in manufacturing in the Amazon is taken as the numeraire in the economy. The parameters of the model are chosen for illustrative purposes and are not calibrated on data. The discount factor is $\delta = 0.96$; the share of consumer expenditures on each of the three goods g is $\alpha_g = 1/3$; the degree of independence in taste shocks for activities within a location is $\lambda = 1$ ($\lambda = 1$ means independence); trade elasticities for all goods g are set to $\theta_g = 1$; the weight of labor expenditure in the production intermediate goods g is set in all regions n to $\gamma_{ng} = 0.8$; the concavity of the deforestation cost is set to $\phi = 0.1$; the fraction of cleared land that returns to forest each period is $\chi = 0.3$.

Figure 5: Goods Price Effects of A Rise in Productivity in Agriculture in the Amazon



Price of Agricultural Goods

Price of Manufacturing Goods

Price of Timber

Price Index of Consumption Goods

Note: All prices are expressed relative to the wage in the manufacturing sector in the Amazon. The bottom right panel shows the price index of consumption goods, defined as the product of the good-specific CES price indices, weighted by their share in consumption expenditures. The parameters of the model are chosen for illustrative purposes and are not calibrated on data. The discount factor is $\delta = 0.96$; the share of consumer expenditures on each of the three goods g is $\alpha_g = 1/3$; the degree of independence in taste shocks for activities within a location is $\lambda = 1$ ($\lambda = 1$ means independence); trade elasticities for all goods g are set to $\theta_g = 1$; the weight of labor expenditure in the production intermediate goods g is set in all regions n to $\gamma_{ng} = 0.8$; the concavity of the deforestation cost is set to $\phi = 0.1$; the fraction of cleared land that returns to forest each period is $\chi = 0.3$.

4.3 Manufacturing productivity in urban centers

Most manufacturing is located in urban areas. As a result, the analysis considers the effect on deforestation of rising manufacturing productivity in urban centers in the Amazon region. Urban areas are different from rural areas in the sense that there is little deforestation potential in cities. Therefore, one would expect the effect of manufacturing productivity growth to have few, if any, adverse effects on deforestation. To explore this question, the following exercise is conducted.

Cities in the Amazon can attract rural workers. The model described in the previous section is extended to account for two subregions in the Amazon: an urban center, with relatively high manufacturing productivity and with very little forest area, and a rural area, with relatively high agricultural productivity and vast forest area. In the first period, the productivity in manufacturing in the urban region (only) is unexpectedly multiplied by two, and remains at this higher level forever. In response to a persistent productivity shock in manufacturing in the urban region occurring in the first period, similar to the one depicted in Figure 2, the economy transitions to a new steady state.

Growth in urban productivity would reduce deforestation. The welfare effects of the manufacturing productivity shock, as well as the effects on deforestation, can be described as follows. Expectedly, welfare in manufacturing rises in the urban region. In fact, the welfare in all sectors increases both in the urban and rural regions. The high manufacturing wages attract mostly workers from the rural areas. This is because the migration cost from the rest of the world to the Amazon's urban region are very high, more so than the cost of transitioning from the agriculture sector in the rural region. This assumption is motivated by the observation that many young rural workers leave their region of birth to find work in urban centers in the Amazon. The population increase in the urban center does not lead to a large increase in demand for the Amazon's agricultural goods, because these are mostly either consumed very locally or exported to the rest of the world. The price of land in the Amazon goes down as local agricultural demand declines due to outmigration. This leads to a decline in deforestation.

However, agricultural value chains within manufacturing pose deforestation risks. Manufacturing growth could spur agricultural competitiveness through value chains and increase deforestation pressure.

5 Discussion of the Expected Effects of Policy Interventions

This section discusses a number of policy interventions that could be undertaken with the goal of limiting deforestation. We use the analysis of the model to describe the expected effects of these policies on the spatial equilibrium. We focus on the effects of (i) increasing educational attainment in the Amazon region, (ii) reducing transportation costs between the Amazon region and global markets, (iii) attracting high-skilled workers through urban planning, (iv) decoupling manufacturing and agricultural value chains, (v) a range of conservation policies.

5.1 Education and training (sectoral switches)

Many manufacturing activities rely on specific skills. As shown by the last modeling exercise, the benefits of manufacturing productivity growth in urban centers can be large for forest conservation if agricultural workers can benefit from the higher paying jobs in manufacturing. This requires agricultural workers to be able to transition relatively easily from farming activities to the manufacturing sector. If few people in the Amazon region are able to acquire skills specific to manufacturing activities, these jobs will be offered to workers who migrate from other regions of Brazil. By not attracting local agricultural workers, the rise of urban manufacturing would not decrease agricultural activity in rural areas and may even raise demand for agriculture if the urban population grows significantly from migration.

Farmers rarely become manufacturing workers. There are several reasons why transitions from farming activities to manufacturing are rare. First, the set of skills required for farming and manufacturing jobs are quite different. Acquiring these skills is likely to be difficult for agricultural workers in rural regions with little access to education and training. Second, agricultural and manufacturing activities are rarely co-located. Farmers willing to work in manufacturing must often migrate to urban centers, sell their farms, find accommodation in cities, and decide whether to move with their households or migrate individually and be separated from their families.

Certain sustainable agricultural practices could help absorb rural labor in the interim, reducing deforestation risks. In the longer term, it is important to prepare rural populations for urban jobs. However, for existing farmers who come under competitive pressures, opportunities can be created within the rural areas—and farmers may find it easier to switch into these. To the extent that these use sustainable methods, deforestation impacts could be minimized. Training programs should help farmers develop the skills for these activities.

Young workers from rural regions often migrate to cities in search of work. Younger workers face lower obstacles to geographic mobility. They are less likely to have dependents and large farm property. Cities offer attractive opportunities for work and careers for young rural workers and contribute to turning them away from subsistence farming and the associated deforestation.

Improving access to education in rural and urban areas in the Amazon could gradually lower deforestation. Better access to education in rural areas would help prepare young rural workers to find jobs in manufacturing and other growing industries. In cities, expanding access to higher education would attract rural students who would then stay and find employment. Expanding access to education and training in rural areas is likely to have a limited effect on incumbent adult farmers, because of the high costs of transitioning from farming to activities in other locations. Hence, improved access to education will lower the pressure on forested land over the medium term, by reducing the inflow of young workers into agriculture.

Uniform improvement in education is needed to prevent re-migration to high-deforestation areas. If better access to education in rural areas is successful at sending young rural workers to urban areas, it may also attract farmers from other regions to replace them. The outflow of rural workers will increase local agricultural wages, and access to education will improve the desirability of raising a family there. The total pressure for land use may then not decline if education is improved in deforestation-prone areas and attracts farmers from non-deforestation-prone areas. To prevent these relocation effects, it is therefore important that access to education is established not only in locations where deforestation is more active, but also in regions where deforestation is not so active.

5.2 Reducing transport costs

Improving transportation networks could increase real incomes but increase deforestation in the Amazon. Transportation infrastructure, principally roads, would increase market access in remote regions of the Amazon by reducing trade and migration costs. Higher integration to goods and labor markets would increase the real income of its residents overall (albeit with an increase in inequality), but is expected to increase deforestation for three reasons.

The selection of large land intensive farmers would increase the demand for land. First, market access is good for farmers' income overall because agriculture is the Amazon's primary export sector. As the second exercise in the previous section showed, agriculture would expand in response to better market access. However, small farmers will be forced to exit and may be worse off. Large farmers will use more land and small farmers will resort more to deforestation, with overall negative consequences for the forest.

The decline of manufacturing centers would make deforestation more attractive. Second, increased market access is beneficial for export-oriented industries, but detrimental to import-oriented industries. This could slow down the gradual exit of young rural workers from rural areas to urban centers. In addition, connecting rural areas to internal markets may lower the price of consumption goods and improve the attractiveness of rural areas relative to already better connected urban areas. All of these would also tend to increase deforestation. Therefore, to avoid higher deforestation risks by reducing transport costs for cities it is important to simultaneously raise the export competitiveness of cities.

Roadsides are a primary locus of deforestation—new rural roads or paving rural roads pose considerable deforestation risks. Third, one immediate effect of opening new roads is to open new pathways to accessing valuable parcels of forest. Roads effectively lower the cost of deforestation of undesignated land. Several studies have emphasized that new roads are associated with an increase of deforestation.

5.3 Urban planning (skills attraction)

Urban planning should focus on productivity, which will reduce deforestation and raise welfare. Better market access will increase the population in the Amazon and this can have ambiguous effects on deforestation. The extension of the transportation network will reduce the remoteness of the Amazon and will attract more workers to the Amazon. This rise in population will increase demand for agricultural products and thus land, leading to an increase in deforestation. As new migrants tend to to locate in cities, migration is unlikely to raise demand for rural land beyond demand arising from higher food demand. However, overall, deforestation effects are likely to be relatively small. For one, the increase in demand for agricultural goods of the larger regional urban centers will be minimal compared to the foreign demand driving most of the agricultural expansion in the Amazon. Second, the increase in population could in fact spur productivity growth in urban centers through agglomeration effects, especially if migrants are relatively skilled. This could lead to a stronger migration from rural to urban Amazon and lower deforestation.

5.4 Industrial policy (agricultural value chains)

Industrial policy should focus on generating an enabling environment for productivity gains, without favoring agricultural value chains. Creating distortions by attracting companies to the Amazon by subsidizing their production (e.g. through tax incentives) is likely to reduce productivity overall which can cause deforestation. Rather, governments should focus on investing in a business climate that all companies can benefit from (including investments in sustainable, productivity-enhancing infrastructure).

Manufacturing value chains with agricultural components can help reduce deforestation if they implement strict certification for sustainability. The rise of the bioeconomy, to the extent that it is able to effectively source its agricultural and forest inputs from non-deforested land, can offer attractive opportunities to farmers engaged in traditional agriculture. As discussed above, without certification for sustainability, the effect of manufacturing growth could be detrimental for the protection of the forest. In this case, limiting the inter-dependence of manufacturing and agriculture value chains in the Amazon would be preferable. Perhaps one of the unintended positive consequences of the Zona Franca of Manaus is that it decoupled the manufacturing and agricultural value chains in the Amazon, by incentivizing manufacturing to rely on imported inputs rather than local agricultural output.

5.5 Breaking the logic of deforestation

Revisiting Figure 1, a conservation lens is applied to study various policies (C) that tackle the drivers of deforestation, as shown in Figure 6:

- **C1a: Incentivize governments to designate undesignated public forests.** Most of illegal deforestation happens on undesignated land, with the prospect of obtaining land titles after several years of occupation. Explicitly designating more forest area for private agricultural use would increase the supply of legally available land. In the model, this can be done by exogenously relabeling part of the stock of forest area into private land. This lowers land prices, reduce speculative motives and illegal deforestation. However, it would increase legal deforestation up to the 20% allowed under the Forest Code. Instead, the land can be designated as public, so that any deforestation is strictly prohibited. This can be evaluated in the model by setting the cost of deforestation to be prohibitive for some of the forest stock. In this case, welfare falls and this encourages illegal deforestation in private, public, or remaining undesignated lands.
- **C1b: Incentivize governments at all levels to enforce environmental protection laws.** The effect of stronger enforcement of environmental protection laws can be

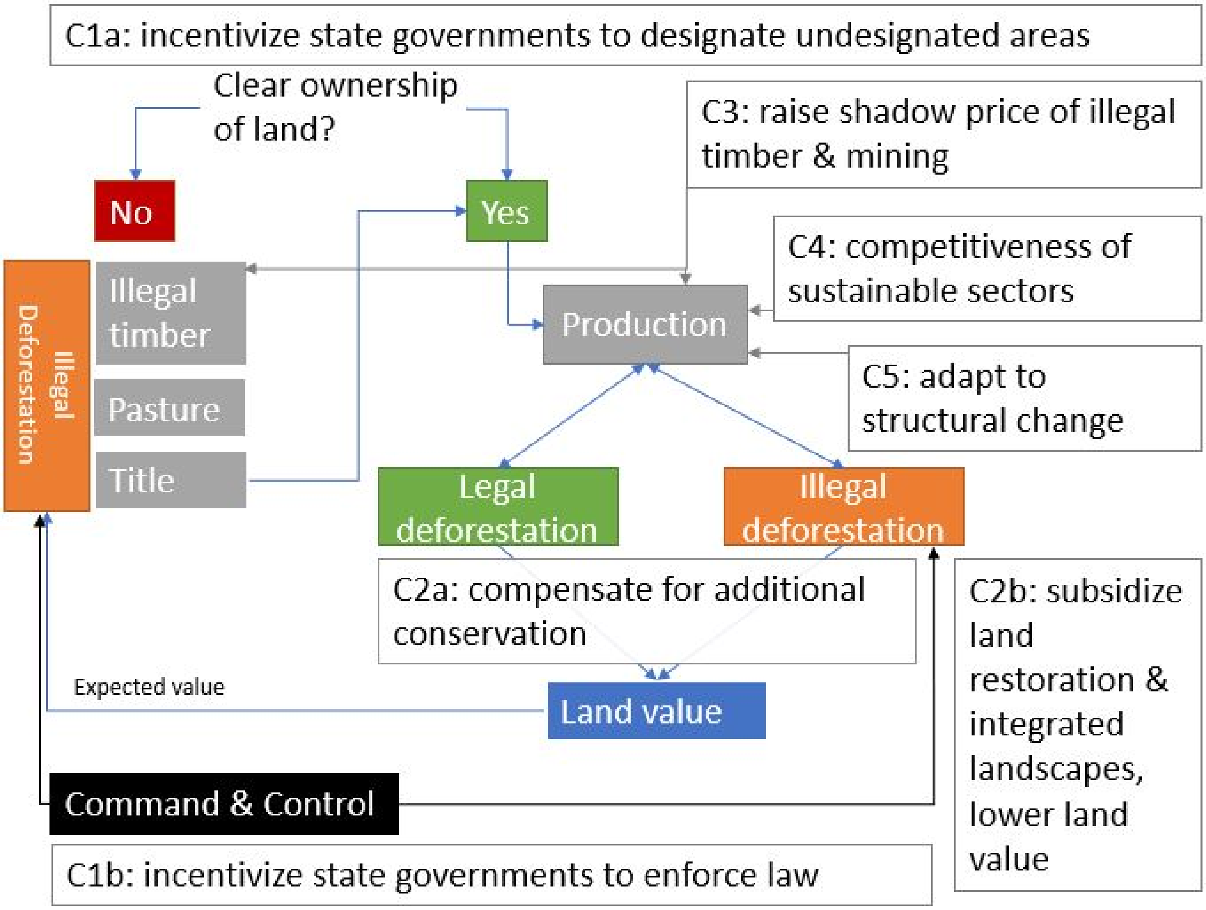


Figure 6: Policies to break the logic of deforestation

evaluated within the model by raising the exogenous component of the cost of deforestation per unit of land. This makes land supply more price inelastic. This reduces welfare (note that welfare does not account for the many environmental benefits of preserving the forest), but encourages agricultural intensification and reduces deforestation. The compensation payment should compensate for this welfare loss to make it politically palatable.

- **C2a: Incentivize landowners to maintain land beyond the limits set by the Forest Code.** Incentives to limit deforestation can be established by directly paying farmers to respect the 80% legal minimum of forested land in their reserve. The model does not account for the individual motive of farmers to deforest above the 20% threshold when monitoring efforts are low enough—instead, it is assumed that farmers respect the 20%-80% rule by default. Hence, transfers to farmers do not have a direct effect of reducing within-parcel deforestation. However, they capture the indirect effect of increasing deforestation of new parcels. As 80% of private land now receives an economic return, the value of owning land increases, fueling speculation motives, and leading to more deforestation. In practice, this policy would be effective at curbing deforestation only if it lowers within-parcel deforestation sufficiently to offset the increase in deforestation of new parcels.
- **C2b: Improve the quality of land, increase the land supply and raise land productivity.** One avenue for increasing the supply of land without increasing deforestation is to provide financing to restoring degraded land. This can be evaluated in the model by lowering the rate at which agricultural land turns into degraded agricultural land. In the short run, this increases land supply, lowers land prices and reduces deforestation. However, if the financing of restoring degraded land is maintained in the long run, this also increases the effective duration of any unit of deforested land as productive agricultural land. This increases the value of engaging in deforestation, raises speculative motives and leads to a decline in the stock of forest in the long run. An alternative policy, more effective in the long run, is to accelerate the transition of degraded land into forest. This allows to convert the stock of non-suitable land, into forest without increasing incentives for deforestation.
- **C3: Incentivize communities to preserve the forest, especially in deforestation hotspots.** In order to limit deforestation, one could provide compensation payments to local communities in exchange for a pledge not to deforest. This can be analyzed in the model by offering subsidies to all individuals who do not engage in deforestation. From the point of view of incentives to residents of the Amazon, this is equivalent to taxing deforestation, and can effectively reduce deforestation. The fiscal burden is of course very different, since compensation would increase workers' income, but require important resources to reach all labor market activities besides deforestation. In addition, it would need to cover most regions of the Amazon, including those with little deforestation, in order to avoid displacing deforestation to areas without compensation (especially if migration costs are low). Finally, it would require perfect monitoring of individual behavior. This would make this both logistically challenging and potentially fiscally unaffordable.
- **C4: Compensate small farmers for structural change.** Market integration and productivity growth in large scale agriculture (e.g., in the form of relatively cheaper fertilizer and machinery) can lead smaller farmers to be displaced and turn to deforestation. Policies can incentivize transitions to manufacturing or more capital-intensive or more sustainable agricultural practices. Technical assistance and skill training are introduced by lowering the cost of transition from unproductive farming to productive farming, and to manufacturing, respectively. With lower transition costs to these alternative activities, small farmers are less likely to engage in deforestation in response to market integration or productivity growth in the productive agriculture sector.

- **C5: Raise the competitiveness of sustainable sectors, especially in cities.** Promoting productivity growth or trade integration of sustainable sectors is an alternative avenue to limit the resort of smaller farmers to deforestation in response to growth in agricultural demand. As shown above with the counterfactual exercise, investing in increasing manufacturing productivity in urban centers in the Amazon (e.g., by investing in information and communication technology infrastructure), can be an effective way to reduce deforestation in the longer run. It offers attractive alternatives to farmers in urban areas in the wake of increasing competitive pressure in the agriculture sector.

6 Conclusion

This paper offers a novel view of the micro-foundations of Amazon deforestation that puts at the forefront the forward-looking motives of deforestation. When the future price of land is high, individuals engage in deforestation, even if the short-term returns to agricultural activity are low. The deforestation decision interacts with individuals' dynamic migration and occupation choices and affects the spatial equilibrium in the Amazon region.

The change of perspective is relevant for policy. Deforestation is both a consequence of an expectation of increased agricultural production (due to greater agricultural demand and agricultural productivity) and a defensive strategy of less productive farmers who come under competitive pressures. This calls for an increased focus on the transition of less productive farmers into alternative rural or urban activities in order to reduce deforestation pressures. The model also shows that deforestation is not simply a rural problem. Regional trade and migration linkages offer a role for urban productivity growth in curbing deforestation. The Amazon's structural transformation will lead to higher urban productivity, providing promising economic alternatives to rural individuals. This will help reduce deforestation, especially if urban sectors have limited connections to agricultural value chains. Infrastructure is critical for both rural and urban productivity growth. Yet, improved market access for agriculture also increases pressure for deforestation. This analysis suggests that a focus on urban competitiveness can be an effective counteracting force. The analysis offers some guidance by testing the theoretical effectiveness of various compensation mechanisms. The current analysis is based on parameter estimates from the literature; future steps will calibrate it to actual data.

References

Azevedo-Ramos, C., P. Moutinho, V. da S. Arruda, M.C.C.Stabile, A. Alencar, I. Castro, and J.P. Ribeiro, "Lawless Land in No Man's Land: The undesignated Public Forests in the Brazilian Amazon," *Land Use Policy*, 2020, *Vol 99.*

Brito, B., J. Almeida, P. Gomes, and R. Salomão., "Dez Fatos Essenciais Sobre Regularizacão Fundiaria na Amazônia Legal," *Imazon, Belém, PA*, 2021.

Caliendo, L., M. Dvorkin, and F. Parro, "Trade and Labor Market Dynamics: General Equilibrium Analysis of the China Shock," *Econometrica*, 2019, *Vol. 87, No. 3*, 741–835.

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

Ferreira-Filho, J.B.S and M. Hanusch, "A Macroeconomic Perspective of Structural Deforestation in Brazil's Amazônia," *Policy Research Working Paper 10162, World Bank, Washington, DC*, 2022.

Sonter, L.J., D. Herrera, D.J. Barrett, G.L. Galford, C.J. Moran, and B.S. Soares-Filho, "Mining Drives Extensive Deforestation in the Brazilian Amazon," *Nature Communications*, 2017, *Vol 8.*

A Solving the Model

$\dot{z}_{t+1} \equiv z_{t+1}/z_t$ denotes the proportional change in any scalar or vector between periods t and $t+1$. Given the allocation of the temporary equilibrium at t, $\{r_t, L_t, \pi_t, X_t\}$, the solution to the temporary equilibrium at $t+1$ for a given change in $\dot{L}_{t+1}$ and $\dot{\Theta}_{t+1}$ does not require information on the level of fundamentals at t, Θ_t, or $\bar{\Theta}$. In particular, it is obtained as the solution to the following system of nonlinear equations

$$\dot{x}_{ngt} = \dot{w}_{ngt}^{\gamma_{ng}} \prod_{g'=1}^{G} \dot{P}_{ng't}^{\gamma_{ngg'}}, \tag{10}$$

$$\dot{P}_{n'gt+1} = \left(\sum_{n=1}^{N} \pi_{n'ngt} \left(\dot{x}_{ngt+1} \dot{\kappa}_{n'ngt+1} \right)^{-\theta_g} \dot{A}_{ngt+1}^{\theta_g \gamma_{ng}} \right)^{-1/\theta_g}, \tag{11}$$

$$\pi_{n'ngt+1} = \pi_{n'ngt} \left(\frac{\dot{x}_{ngt+1} \dot{\kappa}_{n'ngt+1}}{\dot{P}_{n'gt+1}} \right)^{-\theta_g} \dot{A}_{ngt+1}^{\theta_g \gamma_{ng}}. \tag{12}$$

$$\begin{aligned} X_{ngt+1} = & \sum_{g'=1}^{G} \gamma_{ngg'} \sum_{n'=1}^{N} \pi_{n'ng't+1} X_{n'g't+1} \\ & + \alpha_g \left(\sum_{k=1}^{K} \dot{y}_{nkt+1} \dot{L}_{nkt+1} y_{nkt} L_{nkt} + \sum_{k,k'=1}^{K} \rho_{n'k'nkt+1} L_{n'k't} \mu_{n'k'nkt+1} \right), \end{aligned} \tag{13}$$

$$\dot{y}_{nkt+1} = \begin{cases} \dot{w}_{nkt+1} & \text{if } k \in \{1, \dots, J+S\} \\ \dot{w}_{nGt+1} & \text{if } k \in \{J+S+1, \dots, J+2S\} \\ 1 & \text{if } k = K \end{cases} \tag{14}$$

$$\dot{w}_{ngt+1} = \begin{cases} \frac{1}{w_{ngt} L_{ngt+1}} \gamma_{ng} \sum_{n'} \pi_{n'ngt+1} X_{n'gt+1}, & \text{if } g \in \{1, \dots, G-1\} \\ \frac{1}{w_{nGt} \sum_{k=J+S+1}^{J+2S} L_{nkt+1}} \gamma_{nG} \sum_{n'} \pi_{n'nGt+1} X_{n'Gt+1}, & \text{if } g = G \end{cases} \tag{15}$$

A converging sequence of changes in fundamentals is such that $\lim_{t \to \infty} \dot{\Theta}_t = 1$. Further structure is imposed over the instantaneous utility of the agents. In particular, it is assumed that gents have logarithmic preferences, $U(C_{nkt}) = \log(C_{nkt})$. Next, denote $Y_{nkn't} \equiv \exp(IV_{nkn't})$. Moreover, define $u_{nkn'k't} \equiv \exp(U((y_{n'k't} + \rho_{nkn'k't})/P_{n't}) - \tau_{nkn'k't} - d_{n'k't} + \delta V_{n'k't+1})$ and denote by $\dot{\omega}_{nkn'k'}(\dot{L}_{t+1}, \dot{\Theta}_{t+1})$ the equilibrium real incomes in time differences as functions of the change in labor and time-varying fundamentals. Namely, $\dot{\omega}_{nkn'k'}(\dot{L}_{t+1}, \dot{\Theta}_{t+1})$ is the solution to the temporary equilibrium.

Then, conditional on an initial allocation of the economy, $(L_0, \pi_0, X_0, \mu_{-1}, F_0)$, given an anticipated convergent sequence of changes in fundamentals, $\{\dot{\Theta}_t\}$,[7] the solution to the sequential equilibrium in time differences does not require information on the level of the fundamentals $\{\dot{\Theta}_t\}$ or $\bar{\Theta}$ and solves the following system of nonlinear equations:

$$\dot{u}_{nkn'k't+1} = \dot{\omega}_{nkn'k't+1} \dot{\tilde{\tau}}_{nkn'k't+1}^{-1} \dot{\tilde{V}}_{n'k't+2}^{\delta}, \tag{16}$$

$$\dot{\tilde{V}}_{nkt+1} = \frac{1}{NK} \sum_{n'=1}^{N} \dot{\bar{\mu}}_{nkn't+1}^{\lambda-1} \sum_{k'=1}^{K} \frac{\dot{u}_{nkn'k't+1}}{\dot{\mu}_{nkn'k't+1}^{\lambda}}, \tag{17}$$

$$\dot{Y}_{nkn't+1} = \dot{\tilde{V}}_{nkt+1}^{1/\lambda} \dot{\bar{\mu}}_{nkn't+1}^{1/\lambda}. \tag{18}$$

defining $\tilde{V}_{n'k't+1} \equiv \exp(V_{n'k't+1})$, $\tilde{\tau}_{nkn'k't+1} \equiv \exp(\tau_{nkn'k't+1})$ and $\omega_{nkn'k't+1} \equiv (y_{n'k't+1} +$

---

[7] A converging sequence of changes in fundamentals is such that $\lim_{t \to \infty} \dot{\Theta}_t = 1$.

$\rho_{nkn'k't+1})/P_{n't+1}$. The probability of choosing location n' in period t is also defined, conditional on being in location and activity (n, k) at the beginning of period t:

$$\bar{\mu}_{nkn't+1} = \sum_{k'=1}^{K} \mu_{nkn'k't+1}.$$

B Solution Algorithm

Take as given the changes in migration costs $\dot{\tilde{\tau}}_{nkn'k't+1}$, trade costs $\dot{\kappa}_{n'ngt}$, productivity changes $\dot{A}_{ngt}$, the population flows $\mu_{nkn'k'0}$ and stocks L_{nk0}, the wages w_{nj0} and rents r_{ns0} at $t = 0$.

1. For all locations $n = 1, \ldots, N$, activities $k = 1, \ldots, K$, periods $t = 0, \ldots, T$, guess a sequence of value function changes, $\{\dot{\tilde{V}}_{nkt+1}\}$, such that $\dot{\tilde{V}}_{nkT+1} = 1$ for all n, k. As a first guess, define $\dot{Y}_{nkn't+1} = \dot{\tilde{V}}_{nkt+1}^{1/\lambda}$.
2. If there exists an expression for the wages w_{nj1}, price changes $\dot{P}_{nk1}$, and rental rates r_{nk1}, use them in combination with data on wages and rents w_{nj0} and r_{ns0} at $t = 0$ to compute the flows of income. If there is no existing guesses, set $w_{ng1} = w_{ng0}$, $\dot{P}_{n1} = 1$, and $r_{ns1} = r_{ns0}$.
   (a) Then compute the flow of labor income

   $$y_{n'k't} = \begin{cases} w_{n'k't} & \text{if } k' \in \{1, \ldots, J+S\} \\ w_{n'Gt} & \text{if } k' \in \{J+S+1, \ldots, J+2S\} \\ b_{n'} & \text{if } k' = K \end{cases}, \qquad t = 0, 1,$$

   and of net rent payments

   $$\rho_{nkn'k't} = \mathbb{1}_{\{k \in \{J+1, \ldots, J+2S\}\}} r_{nkt} - \mathbb{1}_{\{k' \in \{J+1, \ldots, J+S\}\}} r_{n'k't}, \qquad t = 0, 1,$$

   and use them to compute the real income flow changes $\dot{\omega}_{nkn'k'1}$ as

   $$\dot{\omega}_{nkn'k'1} = \frac{y_{n'k'1} + \rho_{nkn'k'1}}{y_{n'k'0} + \rho_{nkn'k'0}} \frac{1}{\dot{P}_{n'1}}.$$

   (b) Define the utility changes

   $$\dot{u}_{nkn'k'1} = \dot{\omega}_{nkn'k'1} \dot{\tilde{\tau}}_{nkn'k'1}^{-1} \dot{\tilde{V}}_{n'k'2}^{\delta}.$$

   (c) Define the migration shares at $t = 1$, using the data in period $t = 0$

   $$\mu_{nkn'k'1} = \mu_{nkn'k'0} \frac{\dot{u}_{nkn'k'1}^{1/\lambda} \dot{Y}_{nkn'1}^{\lambda-1}}{\dot{\tilde{V}}_{nk1}}, \qquad \forall n, k,$$

   (d) Compute the population stocks in period $t = 1$, using the data in period $t = 0$,

   $$L_{n'k'1} = \sum_{n=1}^{N} \sum_{k=1}^{K} \mu_{nkn'k'1} L_{nk0}, \qquad \forall n', k',$$

   Verify if $L_{ns1} = L_{ns0} + L_{nd_s0}$, where $d_s = s + S$. If not, return to (a) and update r_{ns1} until this relationship is satisfied.

   Reproduce the previous series of steps, iteratively for each period $t \geq 2$, and find the set of rent prices r_{nst} that ensure that the relationship $L_{nst} = L_{nst-1} + L_{nd_st-1}$ holds, conditional on the current guesses of other variables. At the end of this step emerge expressions for the migration shares $\mu_{nkn'k't}$, population stocks $L_{n'k't}$ and rental rates r_{nst} for all time periods.

3. Temporary equilibrium. Find the wage changes $\dot{w}_{ngt+1}$, price changes $\dot{P}_{ngt+1}$, trade flows changes $\dot{\pi}_{n'ngt+1}$, new sales X_{ngt+1} that are consistent with the changes in trade costs $\dot{\kappa}_{n'ngt+1}$, productivity changes $\dot{A}_{ngt+1}$ and initial trade flows $\pi_{n'ngt}$. From the previous step, take as given the population stocks L_{nkt}, the associated population changes $\dot{L}_{nkt}$, the rental rates r_{nst}.
   (a) At $t = 0$, guess a value for $\dot{w}_{ng1}$.
   (b) Compute the unit cost changes $\dot{x}_{ng1}$ and price changes $\dot{P}_{ng1}$ that are consistant with the initial trade flows $\pi_{n'ng0}$, productivity changes $\dot{A}_{ng1}$, trade costs changes $\dot{\kappa}_{n'ng1}$. Iterate on $\dot{x}_{ng1}$ until the following equations are satisfied:

$$\dot{P}_{n'g1} = \left(\sum_{n=1}^{N} \pi_{n'ng0} \left(\dot{x}_{ng1} \dot{\kappa}_{n'ng1} \right)^{-\theta_g} \dot{A}_{ng1}^{\theta_g \gamma_{ng}} \right)^{-1/\theta_g},$$

$$\dot{x}_{ng1} = \dot{w}_{ng1}^{\gamma_{ng}} \prod_{g'=1}^{G} \dot{P}_{ng'1}^{\gamma_{ngg'}}.$$

   (c) Use the unit cost changes $\dot{x}_{ng1}$ and price changes $\dot{P}_{ng1}$ to compute the implied trade flows at $t = 1$:

$$\pi_{n'ng1} = \pi_{n'ng0} \left(\frac{\dot{x}_{ng1} \dot{\kappa}_{n'ng1}}{\dot{P}_{n'g1}} \right)^{-\theta_g} \dot{A}_{ng1}^{\theta_g \gamma_{ng}}.$$

   (d) Use the trade flows at $t = 1$, wage changes $\dot{w}_{ng1}$, initial wages w_{ng0}, rents r_{ns1}, population stocks L_{nk1} and L_{nk0} to obtain (iteratively) the value of sales X_{ng1} from

$$\begin{aligned} X_{ng1} &= \sum_{g'=1}^{G} \gamma_{ngg'} \sum_{n'=1}^{N} \pi_{n'ng'1} X_{n'g'1} \\ &\quad + \alpha_g \left(\sum_{k=1}^{K} \dot{y}_{nk1} y_{nk0} L_{nk1} + \sum_{n'=1}^{N} \sum_{k,k'=1}^{K} \rho_{n'k'nk1} L_{n'k'0} \mu_{n'k'nk1} \right). \end{aligned}$$

   (e) Update the wage changes in order to satisfy the labor market clearing

$$\dot{w}_{nj1} = \frac{1}{w_{nj0} L_{nj1}} \gamma_{nj} \sum_{n'} \pi_{n'nj1} X_{n'j1}.$$

$$\dot{w}_{ng1} = \begin{cases} \frac{1}{w_{ng0} L_{ng1}} \gamma_{ng} \sum_{n'} \pi_{n'ng1} X_{n'g1}, & \text{if } g \in \{1, \ldots, G-1\} \\ \frac{1}{w_{nG0} \sum_{k=J+S+1}^{J+2S} L_{nk1}} \gamma_{nG} \sum_{n'} \pi_{n'nG1} X_{n'G1}, & \text{if } g = G \end{cases}$$

   Once $\dot{w}_{ng1}$ is obtained, along with the associated unit cost changes $\dot{x}_{ng1}$, price changes $\dot{P}_{ng1}$, trade flows $\pi_{n'ng1}$ and sales X_{ng1}, move to solving the temporary equilibrium at $t = 1$. In particular, take as given the trade flows $\pi_{n'ng1}$ implied by the temporary equilibrium at $t = 0$ in order to solve for the temporary equilibrium at $t = 1$. Repeat until reaching $t = T$.

4. Update value function changes.
   (a) With the new expressions for wages w_{ngt}, price changes $\dot{P}_{ngt}$, compute the changes

in real income flows

$$\dot{\omega}_{nkn'k't+1} = \frac{y_{n'k't+1} + \rho_{nkn'k't+1}}{y_{n'k't} + \rho_{nkn'k't}} \frac{1}{\dot{P}_{n'k't+1}}.$$

(b) Starting from $t = T - 1$, compute the utility change, using $\dot{\tilde{V}}_{n'k'T+1} = 1$

$$\dot{u}_{nkn'k'T} = \dot{\omega}_{nkn'k'T} \dot{\tilde{\tau}}_{nkn'k'T}^{-1}$$

Update the value function change at $t = T - 1$:

$$\dot{\tilde{V}}_{nkT} = \frac{1}{NK} \sum_{n'} \dot{\bar{\mu}}_{nkn'T}^{\lambda-1} \sum_{k'} \frac{\dot{u}_{nkn'k'T}}{\dot{\mu}_{nkn'k'T}^{\lambda}},$$

Then for $t = T - 2, \ldots, 0$, iteratively update the value function changes:

$$\dot{u}_{nkn'k't+1} = \dot{\omega}_{nkn'k't+1} \dot{\tilde{\tau}}_{nkn'k't+1}^{-1} \dot{\tilde{V}}_{n'k't+2}^{\delta}.$$

$$\dot{\tilde{V}}_{nkt+1} = \frac{1}{NK} \sum_{n'} \dot{\bar{\mu}}_{nkn't+1}^{\lambda-1} \sum_{k'} \frac{\dot{u}_{nkn'k't+1}}{\dot{\mu}_{nkn'k't+1}^{\lambda}},$$

Also update the inclusive value changes as

$$\dot{Y}_{nkn't+1} = \dot{\tilde{V}}_{nkt+1}^{1/\lambda} \dot{\bar{\mu}}_{nkn't+1}^{1/\lambda}.$$

Check whether the new expression for $\dot{\tilde{V}}_{nkt+1}$ is equal to its initial value. If not, update the value function and return to the first step until convergence.