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Water for Arid Regions: An Economic Geography Approach*

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Abstract: This paper develops a two-region trade model to consider how the uneven allotment of water resources and the availability of interbasin water transfers affect the intraregional distribution of land between urban and agricultural use and the interregional distribution of the population when regions vary in natural amenities, agricultural productivity, and urban agglomeration economies. In each region, urban and agricultural sectors compete over a fixed quantity of land and agricultural goods face transport costs. Three different trade regimes for the agricultural good are considered: autarky, incomplete specialization, and complete specialization. Under autarky, a rise in the agricultural productivity of the water importing region increases the local urban sector. Once regions begin to trade, an increase in the agricultural productivity of the water importing region increases the urban sector in the water exporting region. An increase in natural amenities in the water importing region increases the local urban population driving agricultural production to the less productive water exporting region. Urban agglomeration economies have a small impact when the population is more evenly divided but large impacts when there are large population differences between regions. Reductions in the available supply of water increases both water and agricultural prices and may reduce the quantity of land devoted to agricultural production. A graphical example is presented to show the impact of the parameters on land use patterns, population size and regional prices. The model is then calibrated to reflect stylized facts for California.

Keywords: water, regional land use, trade and geography, local public infrastructure

JEL Codes: Q25, R12, R14, R23, F18

1. INTRODUCTION

Historically, a local supply of water has been a crucial component for the location of cities and agriculture. Indeed, an alternate history of the westward expansion of the United States

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in the 19th century focuses on the Bureau of Land Reclamation and the Army Corps of Engineers struggling to reconfigure existing water resources to accommodate the idiosyncratic land use patterns of the early Western settlers (Reisner, 1993). Increasing urbanization in recent years, particularly in arid regions, has placed considerable stress on their existing water resources. Many regions, in response, have turned to imported water via interbasin transfers to supplement existing resources. Recent research suggests that water transportation infrastructure has greatly reduced the number of water-stressed cities globally (McDonald et al., 2014). Such infrastructure projects can be attractive for regional governments looking to promote growth. For instance, in the 1960's, California Governor Pat Brown inaugurated the State Water Project, which was developed to supply Southern California cities and agriculture with water from the northern part of the state. His stated intention was to "correct an accident of people and geography" (Bourne Jr, 2010). In light of the fact that cities are becoming less reliant on local water sources, this paper presents a novel approach to understanding urban and agricultural water needs across space when water is a mobile factor.

A model is developed to investigate how interbasin water transfers impact the intraregional distribution of land between urban and agricultural use and the interregional distribution of the population when the physical characteristics of land vary between water importing and exporting regions. The model consists of two regions of equal physical size that devote land to either agricultural production or to housing for residents who work in an urban manufacturing sector. Each region is separated by an uninhabitable valley and there are a fixed number of households that gain utility from land, agricultural goods, an urban manufactured good, water, and region-specific natural amenities. There is a fixed quantity of water located solely in one region. A publicly financed water distribution network is developed to transport water across both regions for urban and agricultural use. Each city produces a manufactured good that is freely traded across regions. The manufacturing sector in each region shows increasing returns to scale from a large regional labor force, but urban residents face intracity commuting costs so that urban land rents increase with city size. Agricultural land in each region differs in productivity and there are iceberg transport costs associated with trade in the agricultural good. Households are free to choose their location both across and within regions and a spatial equilibrium is found when individual utility equalizes across regions.

A key issue in this paper is that while interbasin water transfers allow for growth in regions with a limited water supply, how those regions develop will be determined in relation to water exporting regions. For example, suppose two regions are equally effective in producing an agricultural good and intracity commuting costs for workers are low. Furthermore, the water importing region is endowed with greater quality of life amenities. If the agricultural good can be freely transported between regions, the land in the water importing region will be used for urban use, while land in the water exporting region will be devoted to agricultural production. However, if transport costs in the agricultural good are sufficiently high, some land in the water importing region will be devoted to agricultural production, limiting the amount of available land for urban use in the region and leading to urban sectors in both regions, albeit of different sizes. Conversely, suppose each region has the same quality of life amenities, but the water importing region is more productive in terms of the agricultural good. Absent transport costs, the water importing region will be devoted to agricultural production and the water exporting region will be converted to urban use. However, with significant transport costs, the benefits of devoting the more productive region to agriculture are reduced and some agricultural production will be undertaken in the water exporting region. When there are agglomeration economies, so that marginal urban output increases with city size, the uneven regional population distribution determined by the interplay between regional differences in amenities and productivity will be exacerbated. Cities that are initially larger will become even more so, while smaller cities will shrink.

The focus of the paper is limited to the case where one region is endowed with both a more productive agricultural sector and higher level of natural amenities yet is devoid of water resources. Three trade regimes are considered which are dependent on the level of the agricultural productivity differential between both regions: (1) an autarkic regime, where each region produces the agricultural good solely for the local population; (2) incomplete specialization, where local agriculture in the less productive region competes with the agricultural imports of the more productive region; and (3) complete agricultural specialization, where the more productive region is the sole producer of agriculture. A simplified example is considered that allows for a graphical comparative static analysis. The model is calibrated to replicate a number of stylized facts from California and solved numerically to quantify the impact of changes to regional agricultural productivity levels, natural amenities, transport costs, agglomeration economies and available water supply.

The results indicate that agricultural productivity acts as an agglomerative force, where households benefit from allowing the more productive land to be used for agriculture, leading to a concentration of households in the less productive region. However, increases in transport costs or in the natural amenities of the more productive region defuse the agglomerative effect of the agricultural productivity. Economies of scale are found to have little effect when the population is more evenly dispersed; however, increases in agglomeration economies, when the population share differential is high, increases concentration towards the larger region. Reductions in the supply of water raise the price for both water and the agricultural good. Furthermore, when one region specializes in production of the agricultural good, negative shocks to the water supply reduce the quantity of land devoted to agriculture. The numerical results show that when agricultural production is concentrated in one region, agricultural water subsidies lead to a decline in household income and an increase in regional price indices.

From a policy perspective, this research develops a novel framework for considering the allocation of water resources across space as land use patterns adjust to accommodate the location decisions of households. In particular, inherent in the model is the fact that while any location decision is contingent on access to water, interbasin water transfers reduce the severity of that constraint as locations are no longer bound by the *local* supply of water. Water has generally entered into the discussion on trade through the issue of 'virtual water' whereby regions with limited water resources can access goods with high water content through trade with water-rich regions (see Antonelli and Sartori (2015) for a useful survey). Thus a greater supply of water may be a regional source of comparative advantage for the production of water intensive goods (see Ansink (2010) and Debaere (2014)). In contrast, the framework developed in this paper considers how physically transferring water across regions impacts regional development patterns. Additionally, this paper continues in a long tradition of using computable general equilibrium (CGE) models of the monocentric city to explore the effects of policy changes including transportation costs on land rents and congestion (Arnott and MacKinnon, 1977a,b, 1978; Tikoudis et al., 2015), the development of urban subcenters (Sullivan, 1986; Helsley and Sullivan, 1991) and urban environmental policy and land use (Verhoef and Nijkamp, 2002; Bento et al., 2006).

From a theoretical point of view, the model combines the closed monocentric city model Pines and Sadka (1986) and the two-region core-periphery model developed by Krugman (1991) and surveyed in Fujita et al. (2001), and has since provided the basis for the New Economic Geography (NEG). The model is closed in that the total population is fixed while household utility is endogenous and all rental income is redistributed back to households. This allows for welfare analysis under various trade and policy regimes. In addition, the model fixes the quantity of land reflecting the fact that land use is limited by physical or political boundaries. Tabuchi (1998) integrated the Alonso-Muth-Mills model into the NEG framework, however his model retained a central tenet of the monocentric city model that agricultural land rent is exogenous. In contrast, this model, by holding constant the quantity of land available for agricultural or urban use in each region, endogenizes the land rent at the boundary of the city, creating a tension between urban agglomerative processes and increasing agricultural productivity, reinforcing Pflüger and Tabuchi's statement of "the long standing wisdom in spatial economics that ultimately there is only one immobile resource, land" (Pflüger and Tabuchi, 2010). This tension is further reflected in the fact that any land use decision in one region is contingent on the availability of water, which in turn, is determined by the land use decisions in the opposite region. Other authors have explored the effect of limits to developable land on urban growth (Helpman, 1998; Saiz, 2010; Chatterjee and Eyigungor, 2012). However, the effect of heterogeneity in agricultural productivity as a factor in the urban supply of land is not treated. Also relevant is the literature on quantitative spatial economics which extends the Eaton and Kortum (2002) international trade model to explore the spatial distribution of economic activity as in Allen and Arkolakis (2014) and as surveyed in Redding and Rossi-Hansberg (2017)). Gollin et al. (2013), Lagakos and Waugh (2013), and Lagakos et al. (2018) consider international differences in agricultural productivity. However, their analysis focuses on the distribution of labor between agricultural and non-agricultural sectors, which is not considered in this paper.

Picard and Zeng (2005) extend the model of Ottaviano et al. (2002) to integrate more explicitly an agricultural sector with transport costs, which competes with the manufacturing sector for labor. This model, on the other hand, assumes that agriculture competes with the urban households for land and water. Matsuyama (1992) proposed an endogenous growth model that considered both a closed and a small open economy. A positive link was found between agricultural productivity and growth in a closed economy and a negative link in an open setting. Our analysis confirms this result. Under autarky, the more productive region has a larger share of the population and thus a larger manufacturing sector. On the other hand, once trade is possible, the region with less productive agricultural land has a larger manufacturing sector.

A set of papers have focused on how a limited land supply can dampen agglomerative forces (Pflüger and Südekum, 2008; Pflüger and Tabuchi, 2010) In our model, this result occurs due to the tension between households' preferences for natural amenities and agricultural goods. A rise in agricultural productivity has two effects. First, it increases the opportunity cost of urban land while increasing output and thus reducing the price of the agricultural good. On the other hand, when a region is abundant in natural amenities, households are willing to pay a higher rent to locate there, reducing the opportunity cost of urban land. Yet household demand for the agricultural good requires that some land be used for agricultural production and is utilized best in the more productive region. The cumulative effect is to drive up rents at the urban boundary in the region with the more productive agricultural sector.

However, when natural amenities are low, the agricultural productivity effect dominates driving households to the less productive region. This effect is compounded by agglomeration economies as one region becomes relatively more populous than the other, increasing relative wages in favor of the larger region. These results are consistent with the literature on quality of life and urban amenities (Roback, 1982; Rappaport, 2008, 2009). As in Pflüger and Südekum (2008), an intuitively appealing outcome of this model is that, unlike the standard NEG model where at a critical value the whole population goes instantaneously from dispersion to agglomeration, this model shows gradual shifts in the population with changes in productivity. Finally, the model is novel in introducing interregional water transportation infrastructure into the monocentric city and NEG models.

The remainder of the paper is presented as follows. Section 2 develops the model. Section 3 describes the comparative statics under three trade regimes. Section 4 calibrates the model and discusses the numerical simulations. Section 5 concludes and proposes extensions for future research.

2. THE MODEL

Table 1 provides a notational glossary of the terms employed in the model. Consider a small country populated by N identical households. The country is divided into two regions, 1 and 2, respectively, with λN being the endogenous number households in region 1 and $(1-\lambda)N$ the number in region 2. The space of the country is a line of length $2L + L_s$, where L is the size of region $i = 1, 2$ and L_s is a length separating the two regions. The supply of land and water in the country is commonly owned by all residents. Each region contains a monocentric city with an urban manufacturing sector that employs the local population to produce a manufactured good at the central business district (CBD). A share of the land in each region is used for housing the local population with the remaining land devoted to agricultural production. Demand for land by households is fixed at a single unit, which is chosen such that $L = N$. This implies that the size of the city in region 1 is λN and in region 2 is $(1-\lambda)N$, while symmetrically the land devoted to agriculture in region 1 is $(1-\lambda)N$ and in region 2 is λN. The country contains a fixed of supply water, W, located at the CBD of region 2 and used for irrigation by the agricultural sector and by households for personal consumption. The supply of water is assumed to be fully allocated. A publicly financed infrastructure network transports water from the source to households and the agricultural sector in each region.

Table 1: Notational Glossary

a_i	household demand for agricultural good in region i
i	regional subscript
m_i	household demand for manufacturing good
p_i^a	regional agricultural good price
p_i^m	regional manufacturing price, numeraire
p^w	common water price
q	marginal cost of water infrastructure
r_i^a	regional agricultural land rent
$r_i(x_i)$	regional bid-rent function
$\bar{r}$	rental transfer
t	household commuting cost
w_i^a	agricultural water demand per unit of land
w_i^u	household water demand
$\bar{w}$	per-capita supply of water
x_i	distance from the CBD
y_i	regional wage
W_i^a	total regional agricultural water demand
L_i^a	total regional agricultural land
A	shift factor on marginal product of labor
A_i	regional marginal product of labor
I_i	regional net income
L	common length of each region
L_s	distance between regions
N	total population
P_i	regional price indices
T	functional abbreviation
U_i	regional utility level
W	available supply of water
α	water share of agricultural production costs
β_i	regional agricultural productivity
γ	budget share of water
δ	degree of economies of scale in manufacturing sector
η	budget share of manufacturing goods
θ	agricultural water subsidy
λ	share of households in region 1
μ	budget share of agricultural goods
ρ	defines the elasticity of substitution in agricultural production
σ	elasticity of substitution between land and water in agricultural production
τ	agricultural transport costs across regions
ϕ_i	shift parameter denoting household preferences for regions
Φ	functional abbreviation

Figure 1: Regional Space

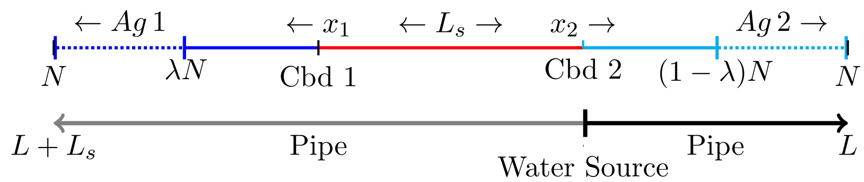


Figure 1 gives a visual description of the space of the model. The top line gives the land distribution. In the center is the length L_s that separates the two regions. At the boundary of L_s and region 1 and 2 is the local CBD. Along the distance x_i is the length of the city, which ends at λN for region 1 and $(1-\lambda)N$ for region 2. The remaining land up to the length N in each region is devoted to agriculture and is denoted in the figure by $Ag1$ and $Ag2$, respectively. The bottom line describes the infrastructure denoted as "Pipe" in the figure. The water supply is located at the CBD of region 2, which travels across the length L of region 2 to the right, while to the left it travels the length $L + L_s$ in order to supply region 1.

2.1. Demand

Each household supplies labor inelastically to the manufacturing sector and receives wage y_i. Households work at the CBD and choose a location of residence x_i in relation to the CBD where they face land rents, $r_i(x_i)$, and commuting costs, tx_i, where t is the marginal cost of commuting in numeraire units. It is assumed that it is costless to migrate within regions, but is prohibitively costly to commute between regions, ensuring that all households work where they live. In addition to wage income, households receive a transfer $\bar{r}$, which is the household share of aggregate land rents, and face the flat tax, f, which is used to finance the water distribution infrastructure. Households have preferences over the numeraire manufacturing good, m_i, urban water, w_i^u, and the agricultural good, a_i, for which they face the agricultural price p_i^a, the common water price p^w, and the price of the manufactured good, p^m, which is set equal to 1. In addition, households benefit from the level of local natural amenities, such as comfortable weather or attractive landscapes, which is captured in the parameter ϕ_i. The household's problem in region i is given by:

$$\max_{a_i, m_i, w_i^u} \phi_i m_i^{\eta} a_i^{\mu} (w_i^u)^{\gamma} \qquad s.t.$$

$$y_i + \bar{r} - tx_i - r_i(x_i) - f = m_i + p_i^a a_i + p^w w_i^u, \quad i = 1, 2, \quad \eta + \mu + \gamma = 1, \tag{1}$$

where η, μ, and γ denote the share of income devoted to the manufactured good, the agricultural good, and urban water, respectively. Demand functions are given by:

$$m_i = \eta I_i, \quad a_i = \mu \frac{I_i}{p_i^a}, \quad w_i^u = \gamma \frac{I_i}{p^w}. \tag{2}$$

The indirect utility function is then

$$V_i(I_i, p_i^a, p^w; \phi_i)) = \phi_i \eta^\eta \mu^\mu \gamma^\gamma \frac{I_i}{(p_i^a)^\mu (p^w)^\gamma}, \tag{3}$$

where

$$I_i \equiv y - tx_i - r_i(x_i) - f, \tag{4}$$

denotes the household income net of rent, government transfers, and taxes. For households to be indifferent across locations in the city, this implies that the derivative of the indirect utility function with respect to x_i be zero, which yields:

$$r_i'(x_i) = -t'. \tag{5}$$

Integrating over x_i gives

$$r_i(x_i) = -tx_i + k, \tag{6}$$

where k is a constant of integration. Using the terminal condition that the rent at the boundary of the city equals the agricultural rent, r_i^a, the bid-rent function for each region can be written as:

$$r_1(x_1) = r_1^a + t(\lambda N - x_1), \quad x_1 \in [0, \lambda N], \tag{7}$$

$$r_2(x_2) = r_2^a + t((1-\lambda)N - x_2), \quad x_2 \in [0, (1-\lambda)N], \tag{8}$$

where use is made of the fact that the boundary of the city in region 1 is λN and $(1-\lambda)N$ in region 2.

2.2. Manufacturing

The manufacturing good is produced by a continuum of small firms, with a linear technology utilizing solely labor. Producers face the wage cost y_i. The aggregate profit function for manufacturing firms in each region is given by:

$$A_1 \lambda N - y_1 \lambda N, \tag{9}$$

$$A_2(1-\lambda)N - y_2(1-\lambda)N, \tag{10}$$

where A_i is the marginal product of labor and is taken as given by firms. The industry is assumed to exhibit increasing returns from regional population size due to agglomeration economies at the aggregate level. This is captured in each region by the term: $A_1(\lambda; \delta) = A(1+\lambda)^\delta$, $A_2((1-\lambda); \delta) = A(1+(1-\lambda))^\delta$. At the firm level, perfect competition drives profit to zero yielding,

$$A(1+\lambda)^\delta = y_1, \tag{11}$$

$$A(1+(1-\lambda))^\delta = y_2, \tag{12}$$

where δ captures the degree of external scale economies from the local population size.

2.2.1. Agricultural Production

Agriculture is organized competitively and is produced using water, W_i^a, and land, L_i^a, with the production function $F(W_i^a, L_i^a; \beta_i) = 2\beta_i\sqrt{W_i^a L_i^a}$. β_i is a region-specific shift factor capturing the productivity of agriculture. It is assumed that $\beta_1 \geq \beta_2$. Given that, in equilibrium, the land devoted to agriculture in each region is simply the share not used by households, with $L_1^a = (1-\lambda)N$ and $L_2^a = \lambda N$, it is useful to write the production function in intensive form as:

$$L_i^a F_i(\frac{W_i^a}{L_i^a}, 1; \beta_i) = L_i^a \left(2\beta_i\sqrt{w_i^a}\right), \tag{13}$$

where w_i^a denotes the demand for agricultural water per unit of land. Producers face the price of water, p^w, and land rent, r_i^a, and charge the price p_i^a. The profit function per unit of land is then:

$$p_i^a\left(2\beta_i\sqrt{w_i^a}\right) - p^w w_i^a - r_i^a. \tag{14}$$

The first-order condition is given by:

$$p_i^a \frac{\beta_i}{\sqrt{w_i^a}} - p^w = 0, \tag{15}$$

which yields the agricultural water demand function per unit of land:

$$w_i^a = \left(\frac{\beta_i p_i^a}{p^w}\right)^2. \tag{16}$$

Perfect competition drives profits to zero, which yields the agricultural land rents:

$$r_i^a = \frac{(\beta_i p_i^a)^2}{p^w}. \tag{17}$$

2.3. The Government

The government plays two roles. First, the government collects land rents and redistributes the proceeds back to residents as a lump sum transfer $\bar{r}$. Second, the government oversees the construction of the water transportation infrastructure, the price of water, and levies a tax on households for any additional costs not covered by the sale of water, f.[1] Note that the assumption of a common flat tax for residents of both regions ensures that there is no migration by households looking to benefit from preferential tax rates.

[1] Note that this specification abstracts from certain key elements in the water distribution process by allowing for a single organization to manage all water distribution across both regions. In practice, local water utilities coordinate with a larger water wholesaler to access interregional transfers.

2.3.1. Rental Transfers

The value of all rental transfers must equal total rental income. We can then write:

$$N\bar{r} = \int_0^{\lambda N} r_1(x_1)dx_1 + \int_{\lambda N}^{N} r_1^a dx_1 + \int_0^{(1-\lambda)N} r_2(x_2)dx_2 + \int_{(1-\lambda)N}^{N} r_2^a dx_2$$
$$= r_a^1 N + r_a^2 N + \frac{tN^2}{2}\left(\lambda^2 + (1-\lambda)^2\right). \quad (18)$$

The rental transfer is then:

$$\bar{r} = r_a^1 + r_a^2 + \frac{tN}{2}\left(\lambda^2 + (1-\lambda)^2\right). \quad (19)$$

2.3.2. Infrastructure Tax

The water transportation infrastructure requires q units of the numeraire good to transport one acre-foot of water one mile. The size of the infrastructure is modeled as proportional to the share of the total water supply going in each direction from the source to region 1 or 2, multiplied by the distance the water must travel. The infrastructure needed to supply each region with water is then:

$$\text{Region 1} : qW(L+L_s) \times \left[\frac{(1-\lambda)Nw_1^a + \lambda Nw_1^u}{W}\right], \quad \text{Region 2} : qWL \times \left[\frac{\lambda Nw_2^a + (1-\lambda)Nw_2^u}{W}\right]. \quad (20)$$

By assumption, the water is fully allocated so the total infrastructure can be rewritten as:

$$qWL + qWL_s\left[\frac{(1-\lambda)Nw_1^a + \lambda Nw_1^u}{W}\right]. \quad (21)$$

The total revenue from the sale of water is simply $p^w W$, thus the per-capita infrastructure tax, [2] after inserting the urban and agricultural water demand functions, can be written as:

$$f = qW\left(1 + \frac{L_s}{N}\left[\frac{(1-\lambda)N\gamma I_1 + \lambda N r_1^a}{p^w \bar{w}}\right]\right) - p^w\bar{w}, \quad (22)$$

where $\bar{w} = \frac{W}{N}$ represents the per capita supply of water and use is made of the fact that $w_i^a = r_i^a/p^w$. The term in brackets indicates the per-capita resources needed to connect the two regions.

Finally, the regional net incomes are given by:

[2]Note that there are no fixed costs with regards to the development of the infrastructure so the Mohring Effect will hold. That is if each agent (agriculture and households in each region) faced a price equal to their marginal cost, the infrastructure costs would be fully recovered. The assumption here is that the government is unable to levy such differentiated prices.

$$I_1 = A(1+\lambda)^{\delta} + r_2^a + tN((1-\lambda)^2 - \frac{1}{2}) + p^w\bar{w} - qW(1 + \frac{\gamma\lambda I_1 + (1-\lambda)r_1^a}{p^w\bar{w}}\frac{L_s}{N}), \quad (23)$$

$$I_2 = A(1+(1-\lambda))^{\delta} + r_1^a + tN(\lambda^2 - \frac{1}{2}) + p^w\bar{w} - qW(1 + \frac{\gamma\lambda I_1 + (1-\lambda)r_1^a}{p^w\bar{w}}\frac{L_s}{N}). \quad (24)$$

2.4. Equilibrium Market Clearing

An additional feature of the model is transportation costs for the agricultural good, which take the iceberg form and are captured by the parameter $\tau \geq 1$. The assumption is that in transit a share of the transported good is lost, so that in order to receive one unit of the good, τ units must be ordered, with the share $\tau - 1$ vanishing in transit. Therefore, the effective price a consumer in region 2 pays for one unit of a good imported from region 1 is $p_2^a = \tau p_1^a$. Given the asymmetries in the location of water and agricultural productivity, it is of interest how the population and thus manufacturing and agricultural production will be distributed across the two regions. *A priori*, it is not possible to know in which direction trade will flow. However, given the assumption that the agricultural sector in region 1 is more productive, the analysis will focus on trade from region 1 to region 2 as productivity increases. We consider three possible regimes: autarky, incomplete agricultural specialization and complete agricultural specialization.

2.4.1. Autarky

An autarkic equilibrium will occur when τ is sufficiently high such that there is no trade between regions. Each region then produces agriculture solely for the local population. Using the agricultural water demand from (16), the regional agricultural goods equilibrium is then:

$$2(1-\lambda)N\frac{p_1^a\beta_1^2}{p^w} = \mu\lambda N\frac{I_1}{p_1^a}, \quad (25)$$

$$2\lambda N\frac{p_2^a\beta_2^2}{p^w} = \mu(1-\lambda)N\frac{I_2}{p_2^a}. \quad (26)$$

These equations determine the equilibrium agricultural price for each region. The government sets the water price to clear the market so that, in equilibrium, the revenue from the sale of water equals expenditure by all urban and agricultural water users, which is given by:

$$p^wW = \gamma(\lambda NI_1 + (1-\lambda)NI_2) + (1-\lambda)N\frac{(\beta_1 p_1^a)^2}{p^w} + \lambda N\frac{(\beta_2 p_2^a)^2}{p^w}. \quad (27)$$

Noting that $r_i^a = p^w w_i^a$, we can solve for the prices as functions of the population shares and income:

$$r_1^a = \frac{\mu}{2}\frac{\lambda}{1-\lambda}I_1, \quad r_2^a = \frac{\mu}{2}\frac{1-\lambda}{\lambda}I_2, \quad p^w = \frac{(\gamma + \frac{\mu}{2})(\lambda I_1 + (1-\lambda)I_2)}{\bar{w}}$$
$$p_1^a = \frac{1}{\beta_1}\sqrt{\left(\frac{\mu}{2}\frac{\lambda}{1-\lambda}I_1\right)\left(\frac{(\gamma + \frac{\mu}{2})(\lambda I_1 + (1-\lambda)I_2)}{\bar{w}}\right)},$$
$$p_2^a = \frac{1}{\beta_2}\sqrt{\left(\frac{\mu}{2}\frac{1-\lambda}{\lambda}I_2\right)\left(\frac{(\gamma + \frac{\mu}{2})(\lambda I_1 + (1-\lambda)I_2)}{\bar{w}}\right)}. \tag{28}$$

2.4.2. Incomplete Agricultural Specialization

Under incomplete agricultural specialization, equilibrium occurs when both regions are agricultural producers, but one region produces in excess of local demand, and trades the remaining share to supplement demand in the other region. In order for trade to occur, the imported price must be no higher than the local price. If both regions are producing, this implies that $p_2^a = \tau p_1^a$. Therefore, market clearing in agriculture is simply that aggregate supply equal aggregate demand:

$$\left(2(1-\lambda)N\frac{p_1^a(\beta_1)^2}{p^w} + 2\lambda N\frac{p_2^a(\beta_2)^2}{p^w}\right) = \mu\left(\lambda N\frac{I_1}{p_1^a} + (1-\lambda)N\frac{I_2}{p_2^a}\right),$$

Note that the different prices for the agricultural good in each region captures the quantity of the good lost in transit. For the share of consumption that region 2 households receive from region 2 producers, there are no transport costs but they pay the price p_2^a. The share of consumption that is imported faces the price p_1^a, but given that to receive 1 unit, a consumer must order τ units. The effective price per unit is $\tau p_1^a = p_2^a$.

The water equilibrium remains as in (27). Solving for prices yields:

$$r_1^a = Br_2^a, \quad r_2^a = \frac{\mu}{2}\frac{\tau\lambda I_1 + (1-\lambda)I_2}{\tau B(1-\lambda)+\lambda}, \quad p^w = \frac{\gamma(\lambda I_1 + (1-\lambda)I_2) + ((1-\lambda)B+\lambda)r_2^a}{\bar{w}},$$
$$p_1^a = \frac{\sqrt{B\left(\frac{\mu}{2}\frac{\tau\lambda I_1+(1-\lambda)I_2}{\tau B(1-\lambda)+\lambda}\right)(\gamma(\lambda I_1 + (1-\lambda)I_2) + ((1-\lambda)B+\lambda)r_2^a)}}{\beta_1}, \tag{29}$$

where:

$$B \equiv \left(\frac{\beta_1}{\tau\beta_2}\right)^2, \tag{30}$$

reflects the relative productivity between regions when transport costs are present. τ in essence allows region 2's agricultural sector to be more competitive by increasing the productivity threshold that the agricultural sector in region 1 must surpass in order to compete in the foreign market

2.4.3. Complete Agricultural Specialization

Complete specialization occurs when β_1 is sufficiently high such that region 1 is the sole agricultural producer. However both regions may continue to produce the manufacturing good, i.e., there may not be complete concentration of the population in one region. As in the case of incomplete specialization, the agricultural price relationship is given by, $p_2^a = \tau p_1^a$. Given that no agriculture is produced in region 2, $r_2^a = 0$ and no agricultural water is used. The agricultural goods equilibrium is then:

$$2(1-\lambda)N\frac{p_1^a(\beta_1)^2}{p^w} = \mu\left(\lambda N\frac{I_1}{p_1^a} + (1-\lambda)N\frac{I_2}{p_2^a}\right), \tag{31}$$

while the water use equilibrium is given by:

$$p^wW = \gamma\left(\lambda NI_1 + (1-\lambda)NI_2\right) + (1-\lambda)N\frac{(\beta_1p_1^a)^2}{p^w}, \tag{32}$$

where region 2's agricultural water use is omitted from Equation (27), the prices can then be written as:

$$\begin{aligned} r_1^a &= \frac{\mu}{2}\left(\frac{\tau\lambda I_1 + (1-\lambda)I_2}{\tau(1-\lambda)}\right), \quad p^w = \frac{\left(\gamma+\frac{\mu}{2}\right)\lambda I_1 + \left(\gamma+\frac{\mu}{2\tau}\right)(1-\lambda)I_2}{\bar{w}}, \\ p_1^a &= \frac{1}{\beta_1}\sqrt{\frac{\mu}{2}\left(\frac{\tau\lambda I_1 + (1-\lambda)I_2}{\tau(1-\lambda)}\right)\frac{\left(\gamma+\frac{\mu}{2}\right)\lambda I_1 + \left(\gamma+\frac{\mu}{2\tau}\right)(1-\lambda)I_2}{\bar{w}}} \end{aligned} \tag{33}$$

2.5. Manufacturing Equilibrium

Equilibrium in the manufacturing sector requires that total output from all urban workers equals total demand for the manufacturing good from households, as well as, the sum of resources needed for aggregate commuting and building the public water infrastructure. Formally, the equilibrium condition is given by:

$$\begin{aligned} &AN((1+\lambda)^\delta\lambda + (1+(1-\lambda))^\delta(1-\lambda)) = \\ &\eta N(\lambda I_1 + (1-\lambda)I_2) + t\frac{N^2}{2}(\lambda^2 + (1-\lambda)^2) + qWL + qWL_s\left[\frac{(1-\lambda)Nw_1^a + \lambda Nw_1^u}{W}\right] \end{aligned} \tag{34}$$

Provided that all other markets are in equilibrium, by Walras' Law, the manufacturing market will be as well.

2.6. Spatial Equilibrium

In the long run, households locate where they can achieve the highest utility. Therefore, a spatial equilibrium occurs when utility equalizes across regions, yielding:

$$\phi_1 \eta^\eta \mu^\mu \gamma^\gamma \frac{I_1}{(p_1^a)^\mu (p^w)^\gamma} = \phi_2 \eta^\eta \mu^\mu \gamma^\gamma \frac{I_2}{(p_2^a)^\mu (p^w)^\gamma}. \tag{35}$$

Equation (35) closes the model by defining the equilibrium population share λ as a function of the model's parameters. The equilibrium number of markets is as follows: in autarky, there are (not including the numeraire, p^m) seven equilibrium prices $\{p^w, p_i^a, r_i^a, y_i\}$, eight allocations $\{a_i, m_i, w_i^u, w_i^a\}$, two government taxes and transfers $\{\bar{r}, f\}$, the equilibrium population share λ, and the common regional utility level U, which yields nineteen endogenous variables. Under incomplete specialization, the number of endogenous variables falls to eighteen with the introduction of trade, which reduces the agricultural goods equilibrium from two equations to one, and the assumption of iceberg transport costs leaves $p_2^a = \tau p_1^a$. Finally, under complete specialization, the absence of an agricultural sector in region 2 discards r_2^a and w_2^a, reducing the number of equilibrium variables to sixteen.

3. COMPARATIVE STATICS

A common criticism of CGE simulations is that the solution procedure is a "black box." One can counter that the theoretical underpinnings of a standard general equilibrium model with constant returns to scale are sufficiently sound, in order to make credible the numerical results of the CGE model, which extend that framework. However, in the case of increasing returns, the criticism becomes more relevant. As shown in the NEG literature, the nonconvexities generated by increasing returns to scale can lead to multiple equilibria, as parameters (in particular, the transport costs) reach critical levels. In addition, the nonconvexities not only vary the number of equilibria but also the stability of each equilibrium. In order to dispel concerns about the robustness of the numerical results, a special case of the model is considered where the production function is Cobb-Douglas, which is simply a special case of the CES production with $\sigma = 1$. The model is then sufficiently tractable, allowing for graphical comparative static analysis of the general equilibrium effects.[3]

This section considers the comparative statics of the equilibrium graphically regarding changes in agricultural productivity β_i, regional amenities ϕ_i, transport costs τ, agglomeration economies δ, and the supply of water W. In addition, comparative statics will be considered under each trade regime. The algebraic details of the solution procedure are provided in Appendix A.

3.1. Autarky

Under autarky, given that prices for water and the manufacturing good are the same across regions, after simplification the spatial equilibrium condition can be written as:

[3] A fully tractable solution is possible if we make the more restrictive assumption that household utility is quasi-linear, which generates no income effects. However, empirical work has shown that income effects matter regarding household demand for water and agricultural goods. Given that this paper aims to address policy concerns, it seems appropriate to reduce the number of assumptions that are simply made for tractability.

$$\phi_1 \frac{I_1}{(p_1^a)^\mu} = \phi_2 \frac{I_2}{(p_2^a)^\mu}, \tag{36}$$

indicating that the population distribution is determined by relative incomes, relative regional agricultural prices (a function of regional agricultural productivity), and relative regional amenities.

Figure 2 plots the effects of changes in β_1, ϕ_1, δ, and W from the symmetric equilibrium as functions of the population share. Each column represents the general equilibrium changes for a single parameter. The top row provides a plot of the spatial equilibrium which pins down the equilibrium population distribution. This value is then traced down to identify the equilibrium prices, which are plotted below as functions of λ. The solid vertical line gives the initial equilibrium while the dashed vertical line traces out the equilibrium after the change in parameter values.

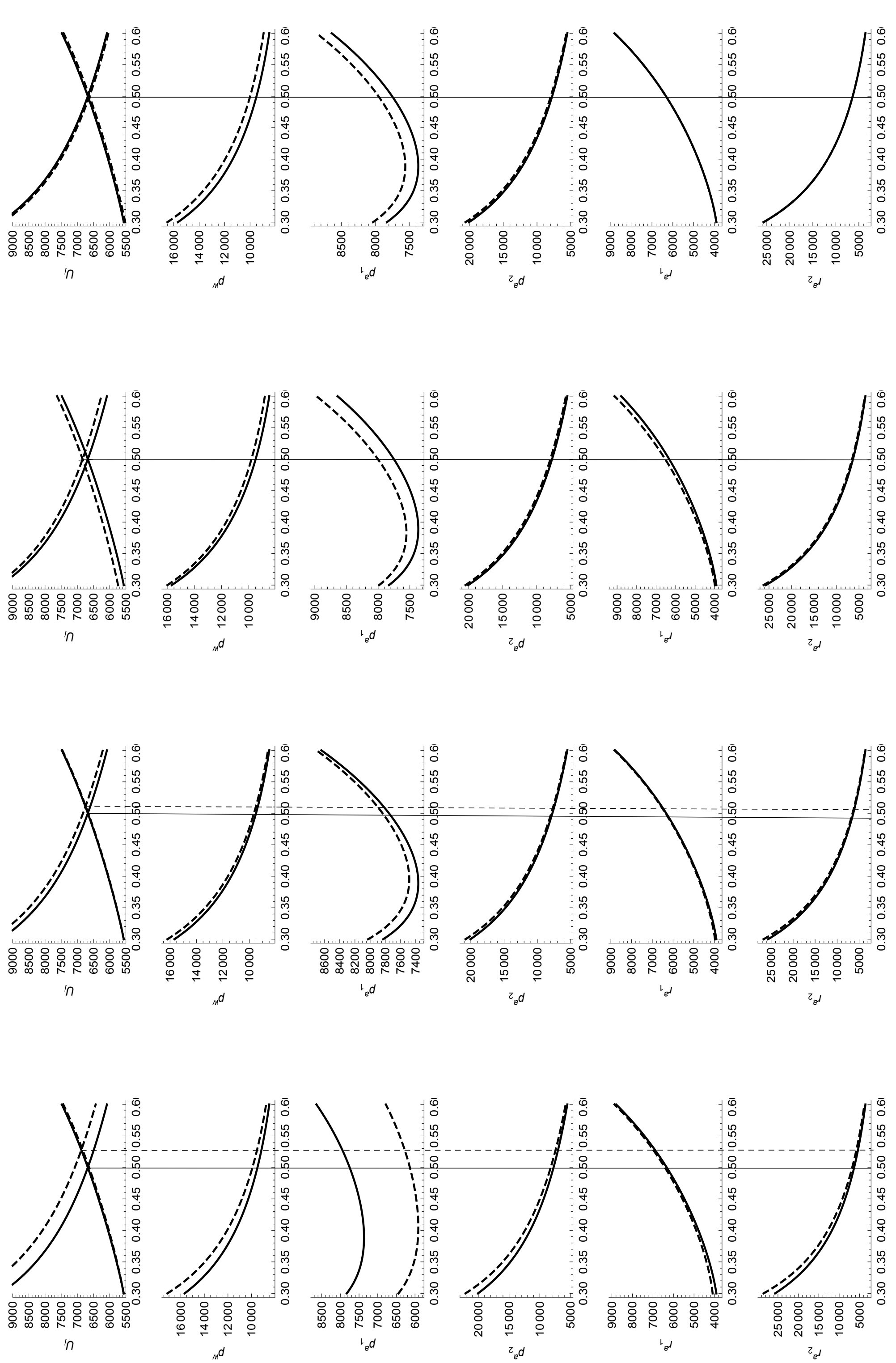
Figure 2a considers the case of a 30 percent increase in β_1 from the equilibrium in which each region is equally productive. When $\beta_1 = \beta_2$, the population and agricultural production are evenly dispersed between regions with each region producing solely for the local population. The first-order effect of a rise in productivity is an increase in agricultural output in region 1, which lowers the regional agricultural price. This raises the utility of households in region 1 relative to region 2, inducing migration, and leads to an increase in λ. In response to the shifts in the population, rents rise in region 1 and fall in region 2. The reduction in agricultural production costs in region 2 generates a fall in the regional agricultural price. In the agricultural sector in region 1, the increase in the local population moves the rental price upwards along the curve increasing production costs. The cumulative effect is a decline in region 1's agricultural price.

Figures 2b and 2c provide comparative statics with respect to ϕ_1 and δ. An increase in natural amenities raises the overall utility level in region 1 inducing migration. However, this leads to an increase in rents in region 1 and a decline in rents in region 2. The cumulative effect is a modest increase in λ. Notice that an increase in δ from the symmetric equilibrium has no effect on the equilibrium values, besides an increase in utility from an increase in manufacturing output. This is due to the fact that when the population is equally dispersed, an increase in δ raises wages equally. Figure 2d provides the impact of a reduction in the available supply of water. While there is a negligible impact on the population distribution, both water and agricultural prices rise due to increases in competition between urban and agricultural users for a smaller quantity of water. In addition, while the regional populations are largely unchanged, there is a reduction in the equilibrium utility level.

3.1.1. Incomplete Agricultural Specialization

Recall that under incomplete specialization the agricultural price relationship is given by, $p_2^a = \tau p_1^a$. Therefore, the spatial equilibrium condition is given by:

$$\phi_1 I_1 = \phi_2 \frac{I_2}{\tau^\mu}, \tag{37}$$



(a) $-\ \beta_1 = 1$, $-\,-\ \beta_1 = 1.3$

(b) $-\ \phi_1 = 1$, $-\,-\ \phi_1 = 1.02$

(c) $-\ \delta = 0$, $-\,-\ \delta = .075$

$-\ W = 20,000$, $-\,-\ W = 19,000$

Comparative statics of equilibrium utility and prices in autarky with respect to (a) β_1, (b) ϕ_1, (c) δ and (d) W

Note: $\beta_2 = 1$, ϕ_2=1, $t = .5$ $\mu = 0.2$, $\gamma = 0.05$, N=20,000, A=50,000, $L_s = L$. All variables are functions of λ

Figure 2

indicating that the population distribution is determined by relative incomes, relative natural amenities, and trade costs which reflect relative agricultural good prices.

Figures 3a-3e trace out the equilibrium for changes in β_1, ϕ_1, τ, δ, and W. Under incomplete specialization, an increase in the agricultural productivity generates more variation in λ than under autarky. The introduction of trade lowers agricultural rents and prices for region 2, which leads migration to shift towards the *less* productive region as β_1 increases. There is an unambiguous decline in p^w, p_1^a, p_2^a, and r_2^a with productivity as the curves shift down and λ falls. An increase in β_1 shifts up the region 1 land rent curve, however this effect is offset by the fall in the local population, and thus there is no significant change in r_1^a. The cumulative effect is that households in region 2 benefit more due to the fall in rent and agricultural prices, leading to a significant shift in the population toward region 2 and an increase in overall utility.

As in autarky, a rise in the natural amenities in region 1 leads to an increase in the local utility level, inducing migration towards region 1. All prices rise as agricultural rents increase in region 1 to accommodate the larger population. In region 2, agricultural rents increase due to a rise in the agricultural price. The increase in the cost of land leads agricultural sectors to substitute land for water, raising the water price.

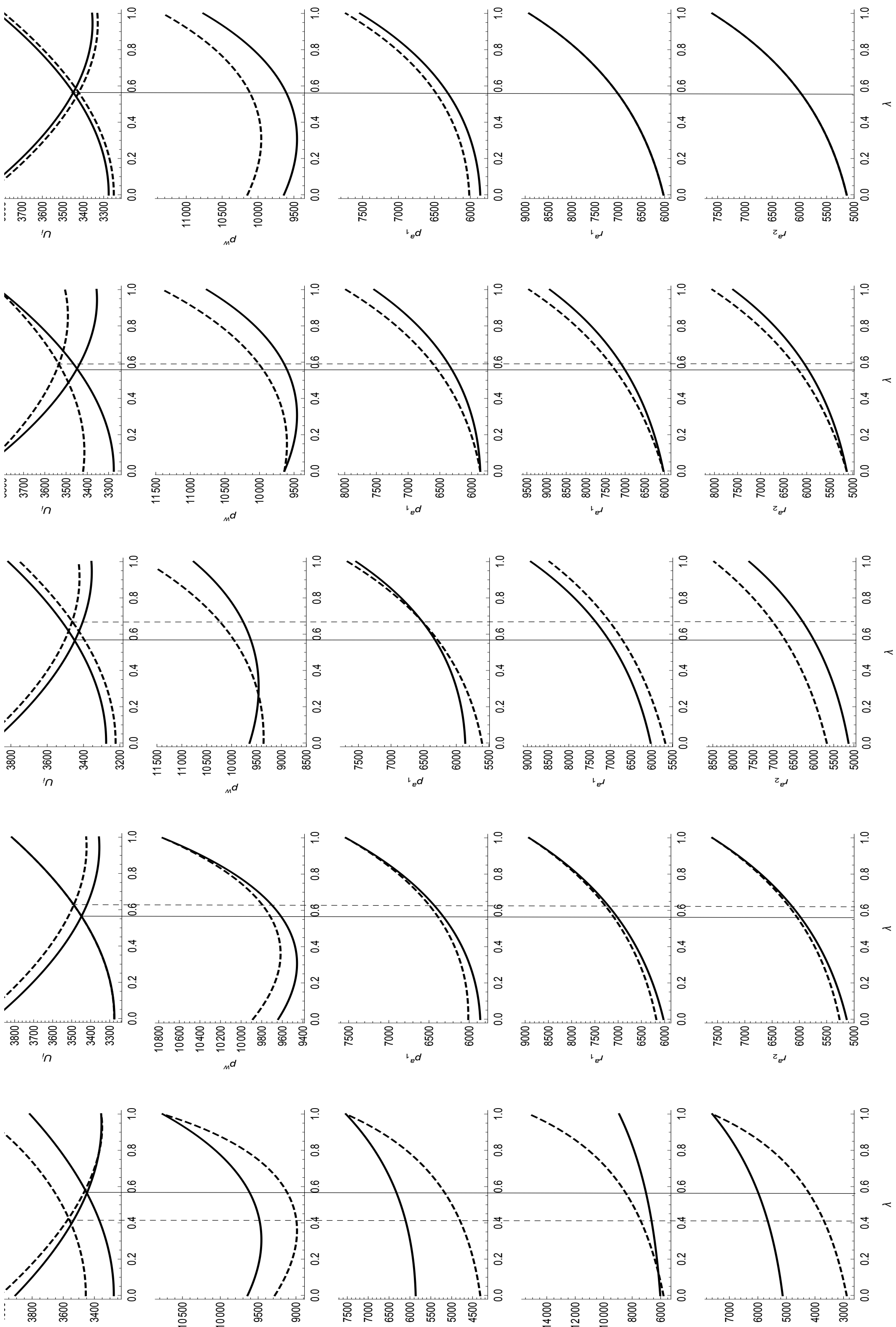
An increase in τ reduces demand for the agricultural good and increases the price index in region 2, inducing migration towards region 1. The cumulative effect is that agricultural prices are largely unaffected while region 1 rents fall due to the drop in foreign demand. Additionally, an increase in τ raises the agricultural price in region 2, increasing the agricultural rent and the demand for water in the region. An increase in δ leads to an increase in all prices as incomes rise. However, given that, in the initial equilibrium, nearly two-thirds of the population were in region 1, the introduction of agglomeration economies favors the more populous region, increasing λ. Finally, the impact of a reduction in water is similar to that of autarky, where both agricultural and water prices rise while utility falls and the population distribution is largely unaffected.

3.1.2. Complete Agricultural Specialization

In the case where only region 1 produces agriculture, $r_2^a = 0$, the spatial equilibrium again is given by:

$$\phi_1 I_1 = \phi_2 \frac{I_2}{\tau^\mu}, \tag{38}$$

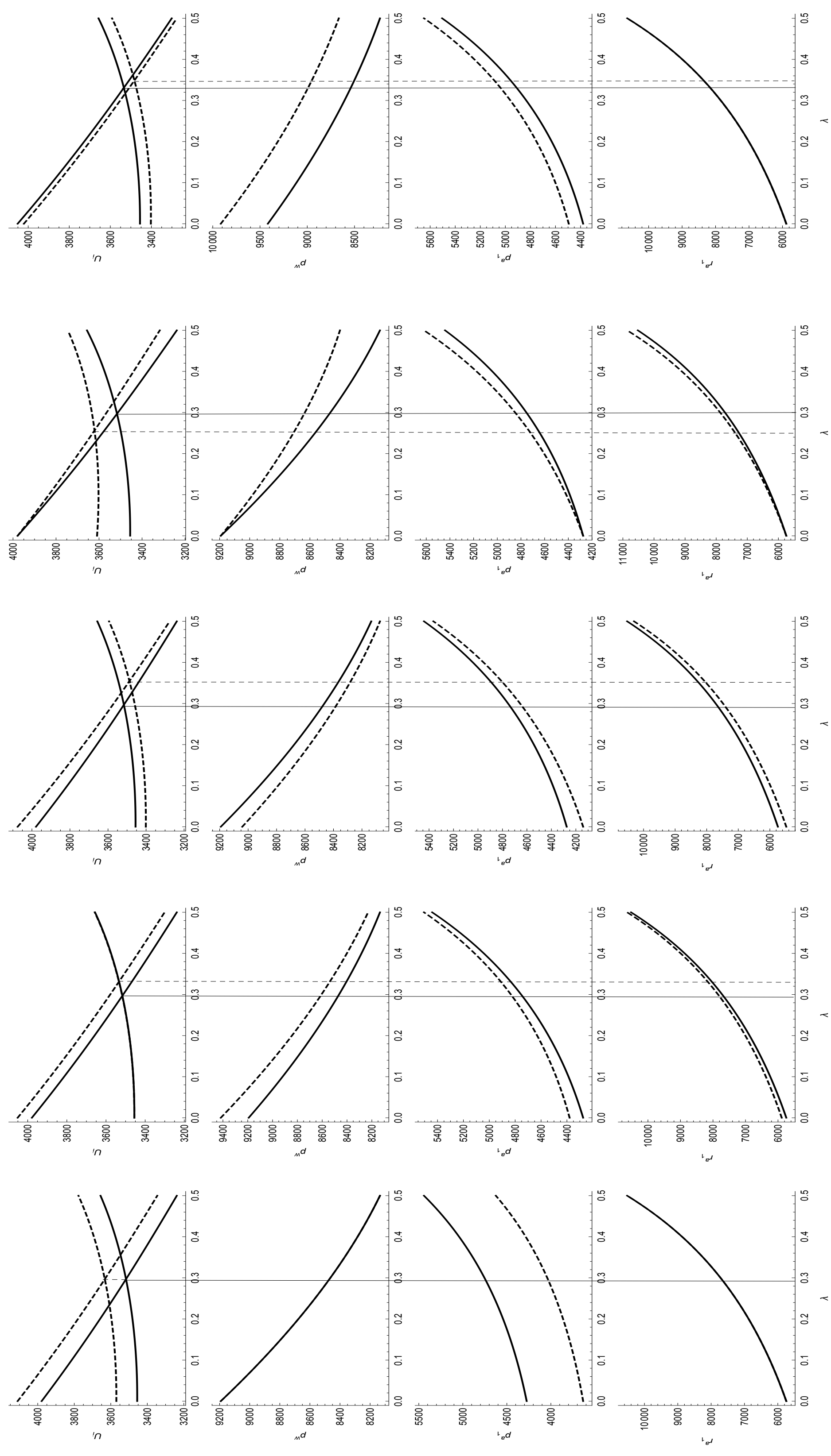
Figures 4a-4e plot the effects of β_1, ϕ_1, τ, δ, and W at equilibrium. Under complete specialization, the majority of households reside in region 2, allowing for region 1 to be primarily used for agricultural production. Notice that while an increase in productivity generates an increase in utility, there is no effect on migration. However, an increase in productivity reduces the agricultural price, raising overall utility. The effects of ϕ_1 are similar to those under autarky and incomplete specialization. A rise in utility generates an increase in λ, which raises agricultural rents and the price for agricultural goods. In response, region 1's agriculture substitutes land for water, increasing p^w.



(a) $-\beta_1 = 1.3$, - - $\beta_1 = 1.7$ (b) $-\phi_1 = 1$, - - $\phi_1 = 1.02$ (c) $-\tau = 1.2$, - - $\tau = 1.3$ (d) $-\delta = 0$, - - $\delta = .075$ $-W = 20,000$, - - $W = 19,000$

Comparative statics of equilibrium utility and prices under incomplete agricultural specialization with respect to (a) β_1, (b) ϕ_1 and (c) τ, (d) δ and (e) W. Note: $\beta_2 = 1$, ϕ_2=1, $t = .5$ $\mu = 0.2$, $\gamma = 0.05$, N=20,000, A=50,000, $L_s = L$. All variables are functions of λ

Figure 3



(a) $-\beta_1 = 1.7$, - - $\beta_1 = 2$ (b) $-\phi_1 = 1$, - - $\phi_1 = 1.02$ (c) $-\tau = 1.2$, - - $\tau = 1.3$ (d) $-\delta = 0$, - - $\delta = .075$ (e) $-W = 20{,}000$ - - $W = 19{,}000$

Comparative statics of equilibrium utility and prices under complete agricultural specialization with respect to (a) β_1, (b) ϕ_1, (c) τ, (d) δ and (e) W. Note: $\beta_2 = 1$, ϕ_2=1, $t = .5$ $\mu = 0.2$, $\gamma = 0.05$, N=20,000, A=50,000, $L_s = L$. All variables are functions of λ

Figure 4

An increase in τ under specialization is largely identical to the case under incomplete specialization. An increase in δ raises all prices. However, the wage increase is greater in region 2 given that the initial population was larger, leading to further migration towards region 2. Figure 4e reveals that a reduction in the available supply of water raises the price of water, agricultural good, and agricultural land rents. This effect lowers household consumption of the agricultural good and reduces the amount of agricultural land necessary to satisfy consumer demand, in turn, increasing the quantity of land devoted to urban use.

4. NUMERICAL RESULTS

In this section, the model is calibrated to exhibit a number of stylized facts for the state of California and is solved numerically. We continue to use all functional forms from Section 3 except the agricultural production function, which takes the constant elasticity of substitution (CES) form:

$$F_i(L_i^a, W_i^a; \beta_i) = \beta_i(\alpha(L_i^a)^\rho + (1-\alpha)(W_i^a)^\rho)^{1/\rho}, \quad -\infty \leq \rho \leq 1, \tag{39}$$

where ρ defines the elasticity of substitution, σ, between land and water, with $\sigma = \frac{1}{1-\rho}$. The reason for doing so is that empirical estimates of the elasticity of substitution between water and land tend to be low. The analysis in the preceding section can be thought of as a special case where $\sigma = 1$. Consistent with empirical estimates (Graveline and Mérel, 2014; Luckmann et al., 2014), σ is set at 0.2, which implies $\rho = -4$. α denotes the share of costs devoted to land and is set at 0.5. The utility share parameters are set at $\eta = .75$, $\mu = 0.2$ and $\gamma = 0.05$ such that the household share of net income devoted to water and agriculture is 25 percent. The marginal cost of commuting t is set such that, in equilibrium where households are evenly dispersed across regions, households who live at the boundary of each city spend 10 percent of their gross income on transportation.

The analysis abstracts from a city with a population density of 10,000 people per square mile, which is consistent with urban population densities for smaller cities in Los Angeles County and the San Francisco/ Bay Area (representative cities with this population density are Berkeley, Santa Monica, East Palo Alto, and Redondo Beach). Therefore, each mile is assumed to hold 100 lots. The length of each region is assumed to be 200 miles long, which implies that the region can hold up to 20,000 individuals. The length of land separating the two regions is assumed to be 60 miles, which makes the length of the country 460 miles. Brandt et al. (2014) estimate that roughly one acre foot of water is used per household in the state of California. Therefore, the total population is set equal to the available water supply in acre feet. The urban agglomeration parameter δ is set at 0.075 (Helsley and Sullivan, 1991; Verhoef and Nijkamp, 2002) while the threshold transport cost τ is set at 1.2 (Volpe et al., 2013). The regional preference parameter ϕ_1 is set at 1.02 while ϕ_2 will be fixed at unity. Due to how ϕ_i enters the utility function, large increases can quickly lead to corner solutions. Therefore ϕ_1 is chosen to ensure interior solutions across all regimes. The agricultural productivity parameter will be fixed at 1 for region 2 and varies between 1 and 2 for region 1, consistent with the United States Department of Agriculture (USDA) data on regional agricultural total factor productivity (TFP) (United States Department of

Table 2: Parameter Values

Benchmark	Base Case	Technology	Free Parameters
$\tau = 1.2$	$\tau = 1.2$	$\eta = 0.75$	$A = 50,000$
ϕ_1 =1	$\phi_1 = 1.02$	$\mu = 0.2$	W=20,000 acre feet
$\delta = 0$	$\delta = .075$	$\gamma = 0.05$	L=200 miles
		$t = 0.5$	$N = 20,000$ households
		$\alpha = 0.5$	$L_s = 60$ miles
		$\theta = 0.6$	
		$\phi_2 = 1$	
		$\beta_2 = 1$	
		$\rho = -4$	

Agriculture, 2017a,b). The parameter values are summarized in Table 2.

The base case is compared to a benchmark model where the only asymmetry is in the regional agricultural productivity (i.e., $\delta = 0$, $\phi_1 = \phi_2$). The benchmark acts as a proxy to show how increasing returns in the agricultural sector and uneven distribution of natural amenities across regions affects the equilibrium outcomes.

To gauge whether the outcomes are efficient, we also consider a social planner's problem. In this case, a social planner chooses the quantity of water and land to devote to agricultural production, the size of the city in each region, and the allocation of final goods to households in order to maximize utility. In Appendix B, we provide a formal derivation of the social planner's problem.

Tables 3-5 present the results of the numerical simulation. Agricultural productivity is varied to analyze how increasing asymmetry in agricultural productivity affects relative prices, water allocation, population shares, and utility. In contrast, one could hold the productivity of land in each region fixed while varying the transport costs τ. Conceptually, the results would be similar. For two regions of different productivity, at high enough transport costs, autarky will hold. As τ is lowered beyond the threshold price ratio, trade will occur. As trade costs become sufficiently low, region 2's agricultural rents will fall to zero leading to all agricultural production being concentrated in region 1.

Since this paper is focused on the heterogeneity between different regions rather than the costs of transport, agricultural productivity is the parameter of variation. The values of β_1 are chosen to ensure consistency of the results across different trade regimes and policy experiments. For the autarkic case, $\beta_1 = 1.3$ ensures that the agricultural price ratio between the regions is below the threshold transport cost and no trade will occur, i.e. $\frac{p_2^a}{p_1^a} < \tau$. $\beta_1 = 1.7$ is sufficiently high to allow for trade while both regions continue to produce agriculture. Finally, in the case of complete specialization, a value of $\beta_1 = 2$ guarantees that there is no agricultural production in region 2.

Table 3: Base Case versus Benchmark and Social Planner

Autarky					
	Base Case	Benchmark	Δ from Benchmark (%)	Social Planner	Δ from Social Planner (%)
a_1	0.98	1.01	-2.95	0.92	6.97
a_2	0.92	0.89	2.92	0.94	-1.52
m_1	48071.19	46763.04	2.80	50927.89	-5.61
m_2	50056.53	48206.76	3.84	51946.39	-3.64
w_1^u	0.24	0.25	-0.12	0.24	2.90
w_2^u	0.26	0.25	0.91	0.24	5.07
w_1^a	0.80	0.79	2.03	0.82	-2.51
w_2^a	0.70	0.72	-1.93	0.65	7.63
p_1^a	13073.01	12342.07	5.92	14814.88	-11.76
p_2^a	14496.20	14368.58	0.89	14814.88	-2.15
r_1^a	4372.00	3840.98	13.83		
r_2^a	2277.10	2439.25	-6.65		
p_1^w	13083.38	12712.27	2.92	14264.90	-8.28
$\bar{r}$	9162.94	8787.08	4.28		
u	3074.42	2970.32	3.50	3162.94	-2.80
λ	0.54	0.53	2.09	0.38	40.15
I_1	64094.92	62350.72	2.80		
I_2	66742.04	64275.68	3.84		
f	-13037.34	-12666.24	2.93		
p_s^w				14264.904	
p_s^a				14814.877	

Note: $\beta_1 = 1.3$

Table 4: Base Case versus Benchmark and Social Planner

Incomplete Specialization					
	Base Case	Benchmark	Δ from Benchmark (%)	Social Planner	Δ from Social Planner (%)
a_1	1.18	1.21	-2.11	1.11	7.17
a_2	1.04	1.05	-0.14	1.13	-7.37
m_1	47619.96	46529.10	2.34	51033.96	-6.69
m_2	50376.21	48257.06	4.39	52054.59	-3.22
w_1^u	0.25	0.25	-0.76	0.24	3.18
w_2^u	0.26	0.26	1.24	0.24	7.02
w_1^a	0.85	0.84	0.81	0.87	-2.15
w_2^a	0.62	0.61	2.19	0.39	60.23
p_1^a	10717.84	10251.82	4.55	12310.60	-12.94
p_2^a	12861.41	12302.19	4.55		4.47
r_1^a	5634.11	5248.02	7.36		
r_2^a	1176.33	1022.71	15.02		
p_1^w	12879.58	12486.73	3.15	14240.61	-9.56
$\bar{r}$	9338.26	8863.02	5.36		
u	3171.48	3069.95	3.31	3289.39	-3.58
λ	0.45	0.40	10.75	0.23	97.05
I_1	63493.28	62038.80	2.34		
I_2	67168.27	64342.75	4.39		
f	-12856.11	-12463.12	3.15		
p_s^w				14240.606	
p_s^a				12310.596	

Note: $\beta_1 = 1.7$

4.1. Base Case versus Benchmark and Social Planner

Table 3 provides the numerical results for the base case in autarky relative to the benchmark and the social planner. As expected, regional incomes and utility rise in the base case relative to the benchmark with the introduction of agglomeration economies, which increases aggregate output and thus regional wages. In the autarkic case, the addition of natural amenities raises the cost of agricultural production in region 1, as agricultural rents rise by nearly 14 percent, leading to a 6 percent increase in the agricultural price and a nearly 3 percent decline in household consumption of the agricultural good. In addition, the rise in rents and agricultural prices leads to an increase in the intensity of water use per unit of land. In region 2, agricultural rents fall by nearly 7 percent and agricultural water use falls by roughly 2 percent per unit of land. However, there is only a modest shift in the population share toward region 1.

As agricultural productivity increases, trade becomes possible between regions as the ratio of agricultural prices rises above the trade barrier τ. As shown in Table 4, in contrast to the autarkic case, relative agricultural rents fall in the base case relative to the benchmark. Introducing natural amenities and agglomeration economies leads to a rise in the agricultural price thus increasing net revenues that can be consumed by the agricultural rent in region 2. Trade pushes households towards region 2, with nearly 60 percent of land in region 1 in the benchmark and 55 percent in the base case devoted to agriculture, as the higher level of natural amenities in region 1 slows migration. Given the relatively small population share differential, the amenity effect dominates the urban economies of scale as relative wages remain roughly the same.

Under complete specialization (shown in Table 5), in contrast to the above cases, agglomeration economies dominate the effect of natural amenities. Given that the population is disproportionately concentrated in region 2, increasing returns in the manufacturing sector leads to a 4 percent higher wage in region 2 inducing further migration.

From the social planner's problem, p_s^w and p_s^a are the normalized shadow prices for water and the agricultural good, respectively. The base case water price is 8 percent below, and the region 1 and region 2 agricultural prices are roughly 12 percent and 2 percent below the social planner's shadow prices in autarky, respectively. The social planner places a significantly lower share of residents in region 1 with nearly two-thirds of the land devoted to agriculture. In addition, each unit of land is used more intensively. In contrast, the base case devotes insufficient resources to the agricultural sector in region 1, while allowing for excessive irrigation in the less productive region 2.

As productivity increases, the social planner continues to devote a larger share of region 1 to agriculture with less than a quarter of land devoted to housing, in contrast to roughly 45 percent used in the base case under incomplete specialization. While water devoted to agricultural production in region 1 is only 2 percent below the social planner, that devoted to region 2 is over 60 percent above, as the social planner drastically reduces the water allocation per unit of land.

Finally, as β_1 reaches 2, the social planner's equilibrium consists of complete concentration of households in region 2 and all land in region 1 devoted to agriculture. Agricultural water per unit of land is higher in the base case under complete specialization, yet total water

Table 5: Base Case versus Benchmark and Social Planner

	Complete Specialization				
	Base Case	Benchmark	Δ from Benchmark (%)	Social Planner	Δ from Social Planner (%)
a_1	1.44	1.45	-0.69	0	
a_2	1.27	1.25	1.29	1.38	-7.91
m_1	48320.23	47110.14	2.57	0.00	
m_2	51117.00	48859.68	4.62	52618.39	-2.85
w_1^u	0.25	0.27	-4.86	0.00	
w_2^u	0.27	0.28	-2.98	0.22	23.61
w_1^a	0.84	0.87	-2.45	0.78	7.63
p_1^a	8959.31	8674.61	3.28	10191.09	-12.09
p_2^a	10751.17	10409.53	3.28		5.50
r_1^a	5458.72	5730.64	-4.75		
p_1^w	12763.39	11836.49	7.83	16238.18	-21.40
$\bar{r}$	7371.05	7557.93	-2.47		
u	3337.07	3222.50	3.56	3430.49	-2.72
λ	0.14	0.16	-15.11	0	
I_1	64426.97	62813.52	2.57		
I_2	68156.00	65146.24	4.62		
f	-12714.23	-11787.27	7.86		
p_s^w				16238.180	
p_s^a				10191.087	

Note: $\beta_1 = 2$

devoted to agriculture is higher under the social planner.

5. CONCLUSION AND FUTURE RESEARCH

This paper developed a spatial two-region general equilibrium trade model to consider how the introduction of interbasin water transfers determines land use patterns in both water importing and water exporting regions when there is heterogeneity between regions in consumption amenities, agricultural productivity, and initial endowments of water. The model was solved analytically for a special case. A numerical simulation was done to allow for a comparison across various policy scenarios. The results suggest that when trade cannot occur, a greater share of the population lives in the more agriculturally productive region. When the same region has the additional benefit of natural amenities, the effect is compounded. As trade is introduced, migration tends toward the less productive region, however, this effect is dampened if the more productive region has a higher level of natural amenities. In addition, economies of scale play a significant role in migration patterns if the population share differential between the two regions is sufficiently high. Reductions in the supply of available water increase the price of both water and agricultural goods. When one region specializes in agricultural production, a negative shock to the water supply reduces the quantity of land devoted to agricultural production.

This research dealt with a very specific problem, namely, how will the uneven distribution of water and the regional variation in agricultural productivity and natural amenities affect land use within regions and the population distribution between regions. However, there are a number of other factors to consider regarding interbasin water transfers. In this analysis, the agricultural good is produced using only water and land. This assumption is reasonable for developed countries where a small fraction of the population is devoted to agricultural production. However, for developing countries it would be important to consider the impact of agricultural productivity on the distribution of workers between employment in agricultural or urban sectors. In particular, an interesting area for future research would be to consider whether transferring water to productive, but arid or semi-arid, regions would reduce the need for agricultural labor allowing for an increase in urban production. In addition, the analysis could consider regional variation in agricultural technology that would allow some regions to utilize water transfers more effectively than others.

An additional feature of the model is that the management of both intraregional and interregional water distribution are handled by a single organization. In practice, there are a number of actors involved at different levels of the water distribution process. For example, in Southern California the Metropolitan Water District (MWD) is the wholesaler for all water transferred from the northern to southern part of the state. MWD then distributes the water to regional water districts and each district then proceeds to distribute water to local residents and firms. At each level there is a different set of infrastructure with varying requirements in terms of size and distance, such that regions closer to the source may benefit more from regional water transfers than those further away. Therefore, an important extension would be to consider the different actors and the spatial relationship between providers and consumers of transferred water in the distribution process.

Another issue is the energy costs associated with pumping water through the network, particularly uphill over mountain ranges. The model could be adapted to take into account topographical irregularities, which would vary the marginal and fixed costs of distribution over space. In addition, one could consider the possibility of electricity generation from the water flow in order to measure net energy use. There are also environmental and ecological concerns related to interbasin water transfers, which may limit the extent to which they can be carried out. Integrating these constraints, in addition to increasing the level of realism, can also highlight alternative conservation methods to stretch existing water resources in the absence of substantial water transfer options. Finally, the model is well equipped to answer the extent to which regions that are water scarce can benefit from imported goods that are water intensive to produce (see Reimer (2012)). As water resources in many regions are becoming increasingly scarce, it will be necessary to identify in what location is water put to best use given the possibility of transport.

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APPENDIX

A. DERIVATIONS OF EQUILBRIUM CONDITIONS IN SECTION 3.3

In this section we derive the equilibrium prices and income levels as functions only of the population shares under each trade regime. Note that in the simulations we choose units so that $L_s = L = N$.

A.1. Autarky

Under autarky the spatial equilibrium condition is given by:

$$\phi_1 \frac{I_1}{(p_1^a)^\mu} = \phi_2 \frac{I_2}{(p_2^a)^\mu}. \tag{A.1}$$

Using Equation (17) we can show that:

$$\frac{p_1^a}{p_2^a} = \frac{\beta_2}{\beta_1}\sqrt{\frac{r_1^a}{r_2^a}} = \frac{\beta_2}{\beta_1}\frac{\lambda}{1-\lambda}\sqrt{\frac{I_1}{I_2}}. \tag{A.2}$$

Inserting this back into (40) yields:

$$\frac{I_2}{I_1} = \left(\frac{\phi_1}{\phi_2}\left(\frac{\beta_1}{\beta_2}\frac{1-\lambda}{\lambda}\right)^\mu\right)^{\frac{2}{2-\mu}} \equiv \Phi. \tag{A.3}$$

The prices laid out in Equation (28) can then be written as functions of I_1:

$$r_1^a = \frac{\mu}{2}\frac{\lambda}{1-\lambda}I_1, \quad r_2^a = \frac{\mu}{2}\frac{1-\lambda}{\lambda}\Phi I_1, \quad p^w = \frac{(\gamma+\frac{\mu}{2})(\lambda+\Phi(1-\lambda))I_1}{\bar{w}}$$
$$p_1^a = \frac{I_1}{\beta_1}\sqrt{\left(\frac{\mu}{2}\frac{\lambda}{1-\lambda}\right)\left(\frac{(\gamma+\frac{\mu}{2})(\lambda+(1-\lambda)\Phi)}{\bar{w}}\right)},$$
$$p_2^a = \frac{I_1}{\beta_2}\sqrt{\left(\frac{\mu}{2}\frac{1-\lambda}{\lambda}\Phi\right)\left(\frac{(\gamma+\frac{\mu}{2})(\lambda+(1-\lambda)\Phi)}{\bar{w}}\right)}.$$

Inserting the prices into Equation (23) yields an equation for I_1:

$$I_1 = \frac{A(1+\lambda)^\delta + tN((1-\lambda)^2 - \frac{1}{2}) - qW(1+\frac{\lambda}{\lambda+(1-\lambda)\Phi})}{1-\frac{\mu}{2}\frac{1-\lambda}{\lambda}\Phi - (\gamma+\frac{\mu}{2})(\lambda+\Phi(1-\lambda))}. \tag{A.4}$$

Finally inserting this equation into Equation (24) yields:

$$I_2 = \left(A(1+(1-\lambda))^{\delta} + tN(\lambda^2 - \frac{1}{2}) - qW(1+\frac{\lambda}{\lambda+(1-\lambda)\Phi}) \right) \\ + \left(\frac{\mu}{2}\frac{\lambda}{1-\lambda} + (\gamma+\frac{\mu}{2})(\lambda+(1-\lambda)\Phi) \right) \frac{A(1+\lambda)^{\delta} + tN((1-\lambda)^2-\frac{1}{2}) - qW(1+\frac{\lambda}{\lambda+(1-\lambda)\Phi})}{1-\frac{\mu}{2}\frac{1-\lambda}{\lambda}\Phi - (\gamma+\frac{\mu}{2})(\lambda+\Phi(1-\lambda))}. \tag{A.5}$$

Inserting Equations (43) and (44) back into Equation (40) gives an implicit equation for λ which pins down the equilibrium prices.

A.2. Incomplete Specialization

Under incomplete specialization the spatial equilibrium condition is given by:

$$TI_1 = I_2, \qquad T \equiv \frac{\phi_1 \tau^{\mu}}{\phi_2}. \tag{A.6}$$

Using the same method as in Appendix A.1 the prices can be written as functions of I_1:

$$r_1^a = Br_2^a, \quad r_2^a = \frac{\mu}{2}\frac{(\tau\lambda+(1-\lambda)T)}{\tau B(1-\lambda)+\lambda}I_1, \quad p^w = \gamma I_1 \frac{\left((\lambda+(1-\lambda)T) + ((1-\lambda)B+\lambda)\frac{\mu}{2}\frac{(\tau\lambda+(1-\lambda)T)}{\tau B(1-\lambda)+\lambda} \right)}{\bar{w}}, \\ p_1^a = I_1 \frac{\sqrt{B\left(\frac{\mu}{2}\frac{\tau\lambda+(1-\lambda)T}{\tau B(1-\lambda)+\lambda}\right)\left(\gamma(\lambda+(1-\lambda)T) + ((1-\lambda)B+\lambda)\frac{\mu}{2}\frac{(\tau\lambda+(1-\lambda)T)}{\tau B(1-\lambda)+\lambda}\right)}}{\beta_1}, \quad p_2^a = \tau p_1^a. \tag{A.7}$$

This yields the income equations

$$I_1 = \frac{A(1+\lambda)^{\delta} + tN((1-\lambda)^2-\frac{1}{2}) - qW(1+\frac{\gamma\lambda+(1-\lambda)B\frac{\mu}{2}\frac{\tau\lambda+(1\lambda)T}{\tau B(1-\lambda)+\lambda}}{\gamma(\lambda+(1-\lambda)T)+((1-\lambda)B+\lambda)\frac{\mu}{2}\frac{\tau\lambda+(1-\lambda)T}{\tau B(1-\lambda)+\lambda}})}{1-\frac{\mu}{2}\frac{\tau\lambda+(1-\lambda)T}{\tau B(1-\lambda)+\lambda}(1+(1-\lambda)B+\lambda) - \gamma(\lambda+(1-\lambda)T)}, \tag{A.8}$$

$$I_2 = \left(A(1+(1-\lambda))^{\delta} + tN(\lambda^2-\frac{1}{2}) - qW(1+\frac{\gamma\lambda+(1-\lambda)B\frac{\mu}{2}\frac{\tau\lambda+(1\lambda)T}{\tau B(1-\lambda)+\lambda}}{\gamma(\lambda+(1-\lambda)T)+((1-\lambda)B+\lambda)\frac{\mu}{2}\frac{\tau\lambda+(1-\lambda)T}{\tau B(1-\lambda)+\lambda}}) \right) \\ + \left(\frac{\mu}{2}\frac{(\tau\lambda+(1-\lambda)T)}{\tau B(1-\lambda)+\lambda} + \gamma\left((\lambda+(1-\lambda)T) + ((1-\lambda)B+\lambda)\frac{\mu}{2}\frac{(\tau\lambda+(1-\lambda)T)}{\tau B(1-\lambda)+\lambda} \right) \right) \\ \times \frac{A(1+\lambda)^{\delta} + tN((1-\lambda)^2-\frac{1}{2}) - qW(1+\frac{\gamma\lambda+(1-\lambda)B\frac{\mu}{2}\frac{\tau\lambda+(1\lambda)T}{\tau B(1-\lambda)+\lambda}}{\gamma(\lambda+(1-\lambda)T)+((1-\lambda)B+\lambda)\frac{\mu}{2}\frac{\tau\lambda+(1-\lambda)T}{\tau B(1-\lambda)+\lambda}})}{1-\frac{\mu}{2}\frac{\tau\lambda+(1-\lambda)T}{\tau B(1-\lambda)+\lambda}(1+(1-\lambda)B+\lambda) - \gamma(\lambda+(1-\lambda)T)}. \tag{A.9}$$

A.3. Complete Specialization

Under complete specialization the spatial equilibrium condition is the same as in Equation (45). Prices can then be written as:

$$r_1^a = \frac{\mu}{2}\left(\frac{\tau\lambda + (1-\lambda)T}{\tau(1-\lambda)}\right) I_1, \quad p^w = \left(\frac{\left(\gamma + \frac{\mu}{2}\right)\lambda + \left(\gamma + \frac{\mu}{2\tau}\right)(1-\lambda)T}{\bar{w}}\right) I_1,$$
$$p_1^a = \frac{I_1}{\beta_1}\sqrt{\frac{\mu}{2}\left(\frac{\tau\lambda + (1-\lambda)T}{\tau(1-\lambda)}\right)\frac{\left(\gamma + \frac{\mu}{2}\right)\lambda + \left(\gamma + \frac{\mu}{2\tau}\right)(1-\lambda)}{\bar{w}}}, \quad p_2^a = \tau p_1^a, \quad r_2^a = 0. \tag{A.10}$$

Finally, net income in each region can be written as:

$$I_1 = \frac{A(1+\lambda)^\delta + tN((1-\lambda)^2 - \frac{1}{2}) - qW\left(1 + \frac{\gamma\lambda + \frac{\mu}{2}(\frac{\tau\lambda + (1-\lambda)T}{\tau})}{(\gamma+\frac{\mu}{2})\lambda + (\gamma + \frac{\mu}{2\tau})(1-\lambda)T}\right)}{1 - \left(\left(\gamma + \frac{\mu}{2}\right)\lambda + \left(\gamma + \frac{\mu}{2\tau}\right)(1-\lambda)T\right)} \tag{A.11}$$

$$\begin{aligned} I_2 = &\left(A(1+(1-\lambda))^\delta + tN(\lambda^2 - \frac{1}{2}) - qW\left(1 + \frac{\gamma\lambda + \frac{\mu}{2}(\frac{\tau\lambda + (1-\lambda)T}{\tau})}{(\gamma+\frac{\mu}{2})\lambda + (\gamma + \frac{\mu}{2\tau})(1-\lambda)T}\right)\right), \\ &+ \left(\frac{\mu}{2}\left(\frac{\tau\lambda + (1-\lambda)T}{\tau(1-\lambda)}\right) + \left(\gamma + \frac{\mu}{2}\right)\lambda + \left(\gamma + \frac{\mu}{2\tau}\right)(1-\lambda)T\right) \\ &\times \frac{A(1+\lambda)^\delta + tN((1-\lambda)^2 - \frac{1}{2}) - qW\left(1 + \frac{\gamma\lambda + \frac{\mu}{2}(\frac{\tau\lambda + (1-\lambda)T}{\tau})}{(\gamma+\frac{\mu}{2})\lambda + (\gamma + \frac{\mu}{2\tau})(1-\lambda)T}\right)}{1 - \left(\left(\gamma + \frac{\mu}{2}\right)\lambda + \left(\gamma + \frac{\mu}{2\tau}\right)(1-\lambda)T\right)}. \end{aligned} \tag{A.12}$$

B. SOCIAL PLANNERS PROBLEM

In this section, we define the social planner's problem that is used in the quantitative analysis in Section 4.

$$\begin{aligned} &\max_{\lambda, W_i^a, w_i^u, a_i, m_i} U_1(m_1, a_1, w_1^u) \quad s.t. \\ &U_1(m_1, a_1, w_1^u) = U_2(m_2, a_2, w_2^u), \\ &F_1(L_1^a, W_1^a; \beta_1) + F_2(L_2^a, W_2^a; \beta_2) - (\tau-1)ES_1 - (\tau-1)ES_2 \geq \lambda N a_1 + (1-\lambda)N a_2, \\ &W \geq W_1^a + W_2^a + \lambda N w_1^u + (1-\lambda)N w_2^u, \\ &\lambda N(A(1+\lambda)^\delta + (1-\lambda)N(1+(1-\lambda))^\delta \geq \lambda N m_1 + (1-\lambda)N m_2 \\ &\quad + qWN(1 + \frac{\lambda N w_1^u + (1-\lambda)N w_1^a}{W}) + \frac{tN}{2}(\lambda^2 N + (1-\lambda)^2 N), \\ &ES_i \geq 0, \quad i = 1,2 \end{aligned} \tag{B.1}$$

where ES_i are excess supply functions for agricultural output in each region:

$$ES_1 = F_1(L_1^a, W_1^a; \beta_1) - \lambda N a_1, \quad ES_2 = F_2(L_2^a, W_2^a; \beta_2) - (1 - \lambda) N a_2.$$

Any excess supply that is exported uses the transport technology such that $(\tau - 1) ES_i$ is lost in transit. Equation (41) is the manufacturing equilibrium. The left-hand side is aggregate output, while the right-hand side is the sum of household demand for manufacturing goods, the water distribution infrastructure, and the household commuting infrastructure.