In Harm's Way? Infrastructure Investments and the Persistence of Coastal Cities

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Abstract

Coasts contain a disproportionate share of the world's population, reflecting historical advantages, but environmental change threatens a reversal of coastal fortune in the coming decades as natural disasters intensify and sea levels rise. This paper considers whether large infrastructure investments should continue to favor coastal areas. I estimate a dynamic spatial equilibrium framework using detailed geo-referenced data on road investments in Vietnam from 2000 to 2010 and find evidence that coastal favoritism has significant costs. The results highlight the importance of accounting for the dynamic effects of environmental change in deciding where to allocate infrastructure today.

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1 Introduction

This paper considers the implications of environmental change for infrastructure investment decisions. A growing literature shows how transport infrastructure investments influence trade costs and hence the distribution of economic activity across space and aggregate growth (Redding and Turner (2015), Allen and Arkolakis (2019), Fajgelbaum and Schaal (2020)). The pattern of gains may, however, be fundamentally affected by a changing climate. An assessment of where infrastructure should be located today may therefore look quite different once the long-term place-making effects of the investments are considered.

I examine this issue by combining a dynamic spatial equilibrium model with detailed geo-referenced micro-data to analyze whether infrastructure investments should continue to favor coastal regions. This is a key question for a range of countries given the significant coastal concentration of both populations and infrastructure. The low elevation coastal zone (LECZ) below 5 meters contains more than 300 million people, accounting for 5% of the world's population in 1% of its land area (CIESIN (2013b)). While this reflects historical natural advantages that coasts enjoy for transport and agriculture (Smith (1776)), coastal advantage may be eroded as development proceeds inland through structural change (Crompton (2004)) and the development of inland transportation networks (Fujita and Mori (1996), Donaldson and Hornbeck (2016)). Looking forward, coastal advantage may even be reversed as a changing climate exposes populations to increasingly severe natural disasters and accelerating sea level rise. Under current projections, the next century will see at least a five-fold increase in the population that experiences coastal flooding annually (Adger et al. (2005)) and a ten-fold increase in flood losses in major coastal cities (Hallegatte et al. (2013)).

Globally, however, coasts continue to attract a large and growing share of major infrastructure investments. I focus on transport infrastructure investments, a significant area of spatial policy accounting for annual spending of over $900bn (Oxford Economics (2015)). The density of major roads in the sub-5m LECZ is more than double the global average (OpenStreetMap, 2016), up from 1.5 times larger based on the best available data from 1980-2010 (CIESIN (2013a)). The contribution of this paper is to consider whether such significant investments in the LECZ represent misallocation and how costly it will be if infrastructure investment decisions fail to account for future sea level rise. This requires an assessment of both the impact of investments on the distribution of economic activity today and their *dynamic* effect on long-run spatial development as environmental change proceeds.

I take this question to the data by collecting detailed information on the economic geography, transport infrastructure investments and projected environmental change in Vietnam. Vietnam is one of the world's most geographically vulnerable countries, facing inundation of 5% of its land area under a 1m rise in sea level - well within the range of forecast increases over the next century (GFDRR (2015)). Yet Vietnam's development strategy continues to favor the growth of urban areas in coastal and low-lying regions (DiGregorio (2013)), which have received a disproportionate share of major infrastructure investments. I consider the effects of road infrastructure improvements from 2000 to 2010, a period of major investment in roads reaching 3.6% of GDP by the end of the period

(ADB (2012)). The left hand panel of Figure 1 shows the spatial distribution of these upgrades, while the right hand panel makes clear that the investments are strongly concentrated in the low elevation coastal zone susceptible to inundation in the coming decades.

I develop a dynamic, multi-region spatial equilibrium model to estimate the aggregate welfare impacts of these infrastructure improvements and study policy counterfactuals in the context of a changing climate. The model incorporates rich geographical heterogeneity which captures the distinct advantages that coastal regions may offer in terms of productivity, amenities and trade links. Between each pair of locations, there are bilateral costs of trade and migration. Households are forward looking and choose where to supply their labor each period, according to a dynamic discrete choice problem building on approaches in Artuç et al. (2010) and Caliendo et al. (2019). The production structure builds on seminal models in the new economic geography literature (Krugman (1991b), Helpman (1998), Kucheryavyy et al. (2016)), incorporating flexible agglomeration externalities and international trade. This setup allows me to model dynamic spatial adjustments as transport investments alter trade costs and future sea level rise inundates land and roads.[1] By incorporating the dynamic effects of infrastructure investments, as well as an environmental damage function, I analyze how future sea level rise will impact on the economic gains from current investments. This is crucial in understanding how growth-creating infrastructure investments and environmental change interact.

I first calibrate the baseline economy and provide evidence that the model performs well in predicting dynamic changes in the spatial distribution of economic activity. Using district-level data in 2010 to solve for relative productivity levels across districts yields calibrated values which over-identification checks suggest provide sensible measures of productivity at the district level. Combining the calibrated values with projections of how future inundation will alter land areas and trade costs as sea level rise takes effect, I then solve the model for each location's equilibrium path of wages and employment and the net present value of welfare. To examine the model's ability to predict dynamic population changes, I use province-level data on 2015 and 2019 population shares that are not used in estimation of the model. The results suggest that the model performs well in predicting endogenous population share changes over time.

The first key result of the paper is that accounting for future sea level rise significantly alters estimates of the returns to infrastructure investments made today. Simulation of the model suggests that the estimated net present value of aggregate welfare gains from realized road investments made in Vietnam from 2000 to 2010 would have been 1.56% ignoring the impacts of future inundation. Accounting for future sea level rise renders these investments significantly less valuable: in a central scenario with a 1 meter rise in the sea level realized gradually over 100 years, estimated gains would be 12% lower at 1.37%. The lower welfare gains in this case reflect the significant share of upgraded roads that are lost to inundation or that connect inundated areas. While a large literature estimates

[1] Desmet et al. (2021) use an alternative approach to estimate endogenous economic adaptations to future sea level rise at the global level, in which dynamic effects arise via local innovation. Relative to Desmet et al. (2021), this paper considers the interaction between current spatial policy investments and future sea level rise in influencing the evolution of the spatial distribution of economic activity and welfare.

the returns to transport upgrading projects in a range of contexts (e.g. Allen and Arkolakis (2014), Alder (2019), Baum-Snow et al. (2018)), this discrepancy suggests that accounting for future climatic changes may substantially alter such estimates in environmentally vulnerable regions.

These results highlight the importance of considering dynamic environmental changes in assessing the gains from realized investments. Such factors are therefore also likely to be important in assessing normative questions of optimal infrastructure placement, the subject of a recent literature using static frameworks (Allen and Arkolakis (2019), Fajgelbaum and Schaal (2020)). To examine this, I use the model to investigate how far the impacts of future sea level rise may affect assessments of where road investments should be targeted today. I achieve this by simulating the effects of several counterfactual investment allocations both with and without accounting for future inundation. The counterfactuals are all based on an objective to maximize pairwise market access – a model-consistent metric that aims to approximate an efficient network in a computationally feasible manner – but are differentially foresighted in the extent to which they avoid vulnerable low-lying areas. In particular, I consider an unconstrained market access maximizing allocation, which is strongly focused in low-lying areas, as well as foresighted allocations which maximize market access while excluding connections to districts with more than 40% or 33% of their land area below 1 meter and as such are less coastally concentrated.

The principal finding of the paper is that taking future sea level rise into account meaningfully changes our assessment of where infrastructure should be allocated today. Simulating the counterfactuals in a scenario without future inundation would suggest that the net present value of aggregate welfare gains from the unconstrained market access maximizing allocation is 2.29%, significantly higher than the 1.80% (1.73%) gains for the foresighted allocations excluding connections to districts with more than 40% (33%) of their land are below 1 meter. In stark contrast, once the effects of future inundation are accounted for, the simulations instead suggest that the 2.34% (2.30%) gains from the foresighted allocations exceed the 2.14% gains from the unconstrained allocation. As such, failing to account for future sea level rise would lead planners to conclude erroneously that the highest welfare gains would be achieved by the unconstrained market maximizing allocation. These results highlight that consideration of future environmental change is central to assessing the returns to, and selecting the efficient allocation of, investments made today.

The fact that higher aggregate long-run welfare gains are available from allocations that avoid the most vulnerable regions relative to otherwise comparable allocations that do not is driven by the foresighted allocations' lower exposure to future inundation. These long-term gains, however, come at the expense of short-run costs of foregoing market access improvements in densely-populated coastal regions in the near term. I consider this dynamic tradeoff through the lens of the model and find that - while welfare gains from the unconstrained market access maximizing allocation dominate gains from the foresighted allocations when the time horizon considered extends up to 2050 - the latter start to dominate as the time horizon over which welfare gains are estimated increases beyond this. This points to a potentially important role for policy myopia in driving dynamically sub-optimal infrastructure placement in the context of a changing climate.

The historical experience of several major cities, such as Mexico City or New Orleans, has shown that historical population movements towards geographically hazardous areas can store up catastrophic consequences for the future, long after obsolescence of their original natural advantages (Vigdor (2008)). This paper finds that current patterns of urban development in developing countries - which will define the major cities of the future - may similarly be failing to reflect changing economic conditions and climate risks. Deciding how to allocate the enormous investments being made in infrastructure and other spatially-targeted policies across developing countries represents a major policy challenge. The results of this paper highlight that it will be crucial to ensure that these allocations take account of the dynamic effects of future environmental change.

The remainder of the paper is structured as follows. Section 2 introduces the quantitative spatial model used to study the effects of road upgrades. Section 3 describes the data used in the analysis and uses this to present motivating facts relating to changing coastal advantage and road investments in Vietnam. Section 4 describes the parameterization of the model and calibration of district-level values for market access and relative productivities in an initial period. Section 5 describes the estimation procedure used to solve the model and quantify the returns to realized road investments made in Vietnam between 2000 and 2010 with and without accounting for the effects of future sea level rise. Section 6 simulates the dynamic welfare gains from a series of counterfactual road allocations which anticipate future sea level rise to varying degrees. Section 7 concludes.

2 Theoretical Framework

I develop a multi-region quantitative spatial equilibrium framework to study the importance of accounting for the dynamic effects of environmental change in deciding where to allocate infrastructure. This setup captures general equilibrium effects of transport improvements and thus allows me to distinguish reallocation from growth and measure aggregate welfare impacts. While the spatial equilibrium literature has to date focused predominantly on static models, this paper considers the effects of *future* changes in economic geography and as such asks questions that are inherently dynamic. I therefore incorporate approaches pioneered in recent dynamic rational-expectations spatial trade models in Artuç et al. (2010) and Caliendo et al. (2019).

The production structure builds on seminal models in the new economic geography literature (Krugman (1991b), Helpman (1998), Redding (2016)), in which firms in each location use labor to produce horizontally-differentiated goods varieties under conditions of monopolistic competition and increasing returns to scale. Following Kucheryavyy et al. (2016), I consider a generalized version of the model which permits greater flexibility in agglomeration externalities by allowing the elasticity of substitution across varieties from different locations to differ from that across varieties from the same location. Bilateral goods trade between each pair of locations, and between each location and foreign markets, is subject to iceberg trade costs which depend on the transport network each period.

2.1 Model setup

The economy consists of several locations indexed by $i, n \in N$ over discrete time periods $t = 0, 1, 2, ...$ Locations differ in terms of their productivity $A_{n,t}$, amenity value $B_{n,t}$, supply of (immobile) land $H_{n,t}$ and initial endowment of (imperfectly mobile) workers $L_{n,0}$. The productivity terms $A_{n,t}$ represent features that make different regions more or less attractive in terms of the costs of production, which may include natural advantages (such as proximity of natural resources) or induced advantages (such as infrastructure). Local amenities $B_{n,t}$ capture characteristics of each location that make them more or less desirable places to live.

2.2 Consumer preferences

Workers are each endowed with one unit of labor each period, which they supply inelastically with zero disutility in the region in which they start the period. During each period t, agents work, earn the market wage and consume consumption goods $C_{n,t}$ and land $H_{n,t}$ in the location n in which they start the period. They have idiosyncratic preference shocks $b_{n,t}$ for each location which are independently and identically distributed across individuals, locations and time.

Workers are forward looking and discount the future with discount factor $\beta \in (0, 1)$. At the end of each period, they may relocate to another location, whose amenity value they will enjoy and where they will work next period. However, migration across space is subject to an additive migration cost, which depends on the locations of origin and destination according to the bilateral cost matrix μ_{ni}, which is assumed time-invariant.[2] This migration cost contributes to persistence in location choice, since workers incur a utility cost of relocating to any location other than their location of origin. Labor is immobile across countries.

The dynamic lifetime utility maximization problem of a worker in location n at time t is therefore:

$$v_{n,t} = \alpha ln\left(\frac{C_{n,t}}{\alpha}\right) + (1-\alpha)ln\left(\frac{H_{n,t}}{1-\alpha}\right) + max_{i\in N}\left[\beta\mathbb{E}\left(v_{i,t+1}\right) - \mu_{in} + B_{i,t} + b_{i,t}\right],\ 0 < \alpha < 1$$

The goods consumption index $C_{n,t}$ is defined over an endogenously-determined measure $M_{i,t}$ of horizontally differentiated varieties supplied by each location. Preferences are CES across location bundles with an elasticity of substitution η and CES across varieties within a location bundle with elasticity of substitution σ.

Following Artuç et al. (2010), the idiosyncratic preference shocks $b_{n,t}$ are assumed to follow a Gumbel distribution with parameters $(-\gamma\nu, \nu)$, where γ is Euler's constant. Based on this assumption, it is shown in Appendix D that the expected lifetime utility of a representative agent at location n is given by the sum of the current period utility and the option value to move into any other market

[2] The model incorporates costly internal migration in light of evidence that such costs are important in a number of developing countries (Au and Henderson (2006b), Bryan and Morten (2018)), and likely to be so in my empirical setting (Anh (1999)).

for the next period, where the expectation is over preference shocks:

$$V_{n,t} = \mathbb{E}\left(v_{n,t}\right) = \alpha ln\left(\frac{C_{n,t}}{\alpha}\right) + (1-\alpha) ln\left(\frac{H_{n,t}}{1-\alpha}\right) + \nu ln \sum_{i\in N}\left(exp\left[\beta V_{i,t+1} - \mu_{in} + B_{i,t}\right]\right)^{\frac{1}{\nu}} \quad (1)$$

The distribution of the idiosyncratic preference shocks also yields an equation (derived in Appendix D) for the share of workers who start period t in region n that migrate to region i:

$$m_{in,t} = \frac{\left(exp\left[\beta V_{i,t+1} - \mu_{in} + B_{i,t}\right]\right)^{\frac{1}{\nu}}}{\sum_{m\in N}\left(exp\left[\beta V_{m,t+1} - \mu_{mn} + B_{m,t}\right]\right)^{\frac{1}{\nu}}} \quad (2)$$

As such, *ceteris paribus*, higher expected lifetime utilities and local amenities attract migrants while higher migration costs deter them, with a migration elasticity equal to $\frac{1}{\nu}$. The evolution of the population in each location across time can be obtained using these migration shares and the distribution of the population across regions in an initial period, $L_{i,0}$, according to:

$$L_{n,t+1} = \sum_{i\in N} m_{ni,t} L_{i,t} \quad (3)$$

2.3 Production, prices and trade

Production is characterized by a static optimization problem that can be solved for equilibrium wages and prices given the supply of labor available in each location at every time period t.

Different varieties of goods are produced under conditions of monopolistic competition and increasing returns to scale, in line with the new economic geography literature. Increasing returns arise from the requirement that, in order to produce a variety j in a location i, a firm must incur a fixed cost of F units of labor as well as a variable cost that depends on productivity $A_{i,t}$ in the location. The number of labor units required to produce $x_{i,t}(j)$ units of variety j in location i at time t is therefore $l_{i,t}(j) = F + \frac{x_{i,t}(j)}{A_{i,t}}$. Goods produced are imperfectly mobile across locations, with bilateral goods trade costs taking the iceberg form such that $d_{ni,t}$ units of a good must be shipped from location i for one unit to arrive in location n, where $d_{ni,t} \geq 1$ for $\forall i, n, t$. Increasing returns to scale in production and costly trade, combined with consumer love of variety, result in agglomeration economies in the form of pecuniary externalities.

Appendix D derives the following expressions for the consumption goods price index, $P_{n,t}$ and trade shares $\pi_{ni,t}$:

$$P_{n,t}^{1-\eta} = \sum_{i\in N}\left(\frac{L_{i,t}}{\sigma F}\right)^{\frac{1-\eta}{1-\sigma}}\left(\left(\frac{\sigma}{\sigma-1}\right)\frac{d_{ni,t} w_{i,t}}{A_{i,t}}\right)^{1-\eta} \quad (4)$$

$$\pi_{ni,t} = \left(\frac{P_{ni}}{P_n}\right)^{1-\eta} = \frac{X_{ni,t}}{X_{n,t}} = \frac{L_{i,t}^{\frac{1-\eta}{1-\sigma}}\left[\frac{d_{ni,t} w_{i,t}}{A_{i,t}}\right]^{1-\eta}}{\sum_{l\in N} L_{l,t}^{\frac{1-\eta}{1-\sigma}}\left[\frac{d_{nl,t} w_{l,t}}{A_{l,t}}\right]^{1-\eta}} \quad (5)$$

where $w_{i,t}$ is the wage in location i, $X_{ni,t}$ is the total value of bilateral trade flows from location i to location n and $X_{n,t}$ is aggregate expenditure at n at time t.

2.4 Income

Let $y_{n,t}$ be the nominal income per labor unit and $r_{n,t}$ the land rent at location n at time t.[3] A worker who starts the period at n will then receive real income:

$$Y_{n,t} = \frac{y_{n,t}}{P_{n,t}^{\alpha} r_{n,t}^{1-\alpha}} \tag{6}$$

Following Monte et al. (2018), I assume that land in each location is owned by immobile landlords who receive worker expenditure on residential land as income and only consume goods in the location in which they live. As a result, workers' nominal income consists of their wage income only:

$$y_{n,t} L_{n,t} = w_{n,t} L_{n,t} \tag{7}$$

Land market clearing ensures that land income must equal expenditure on land, yielding an expression for the equilibrium land rent:

$$r_{n,t} = \frac{(1-\alpha) y_{n,t} L_{n,t}}{H_{n,t}} = \frac{(1-\alpha) w_{n,t} L_{n,t}}{H_{n,t}} \tag{8}$$

This implies that the expected lifetime utility of a representative worker in location n at time t in equation (1) can be expressed as:

$$V_{n,t} = \alpha ln w_{n,t} - \alpha ln P_{n,t} - (1-\alpha) ln \left(\frac{(1-\alpha) L_{n,t}}{H_{n,t}} \right) + \nu ln \sum_{i \in N} \left(exp \left[\beta V_{i,t+1} - \mu_{in} + B_{i,t} \right] \right)^{\frac{1}{\nu}} \tag{9}$$

2.5 International trade

While the framework described above is amenable to incorporating inter- as well as intra-national trade, quantitative analysis in this case requires data on wages, population, land area and bilateral transport costs for all foreign as well as domestic trading partner regions. To circumvent this, I employ the convenient method outlined in Baum-Snow et al. (2018) in their exposition of the canonical model in Eaton and Kortum (2002) with trade both across countries and between regions within countries, which requires only data on the total value of the country's international exports and bilateral trade costs from each region to the nearest international port.

Continuing with the notation above but now indexing domestic regions by i, k, n and the rest of the world by x, the share of region n's expenditure on goods from region i at time t in a world with

[3] Income is the same across all workers in a location as a result of competitive labor markets.

international trade is:

$$\pi_{ni,t} = \frac{L_{i,t}^{\frac{1-\eta}{1-\sigma}} \left(\frac{d_{ni,t}w_{i,t}}{A_{i,t}}\right)^{1-\eta}}{\sum_{k\in N} L_{k,t}^{\frac{1-\eta}{1-\sigma}} \left(\frac{d_{nk,t}w_{k,t}}{A_{k,t}}\right)^{1-\eta} + L_{x,t}^{\frac{1-\eta}{1-\sigma}} \left(\frac{d_{nx,t}w_{x,t}}{A_{x,t}}\right)^{1-\eta}} \tag{10}$$

and the price index is now given by:

$$P_{n,t}^{1-\eta} = \left(\frac{\sigma}{\sigma-1}\right)^{1-\eta} \left(\frac{1}{\sigma F}\right)^{\frac{1-\eta}{1-\sigma}} \left[\sum_{i\in N} L_{i,t}^{\frac{1-\eta}{1-\sigma}} \left(\frac{d_{ni,t}w_{i,t}}{A_{i,t}}\right)^{1-\eta} + L_{x,t}^{\frac{1-\eta}{1-\sigma}} \left(\frac{d_{nx,t}w_{x,t}}{A_{x,t}}\right)^{1-\eta}\right] \tag{11}$$

Combining these equations and substituting $\pi_{ni,t} = \frac{X_{ni,t}}{X_{n,t}}$ yields expressions for total international imports I (the value of all trade flows from the rest of the world to domestic locations) and total international exports E (the value of all trade flows from domestic locations to the rest of the world) in time period t:

$$I_t = \frac{L_{x,t}^{\frac{1-\eta}{1-\sigma}} \left(\frac{w_{x,t}}{A_{x,t}}\right)^{1-\eta}}{(\sigma F)^{\frac{1-\eta}{1-\sigma}} \left(\frac{\sigma}{\sigma-1}\right)^{\eta-1}} \sum_{n\in N} \frac{{d_{nx,t}}^{1-\eta} X_{n,t}}{P_{n,t}^{1-\eta}} \tag{12}$$

$$E_t = \frac{X_{x,t}}{P_{x,t}^{1-\eta} (\sigma F)^{\frac{1-\eta}{1-\sigma}} \left(\frac{\sigma}{\sigma-1}\right)^{\eta-1}} \sum_{n\in N} L_{n,t}^{\frac{1-\eta}{1-\sigma}} \left(\frac{d_{xn,t}w_{n,t}}{A_{n,t}}\right)^{1-\eta} \tag{13}$$

For markets to clear, the total income of location i must equal the total expenditure of location i, denoted as above by $X_{i,t}$. Total income at location i is equal to the total expenditure on goods produced in location i, including exports to both domestic locations (indexed by n) and to the rest of the world (indexed by x):

$$X_{i,t} = \sum_{n\in N} \frac{L_{i,t}^{\frac{1-\eta}{1-\sigma}} \left(\frac{d_{ni,t}w_{i,t}}{A_{i,t}}\right)^{1-\eta}}{P_{n,t}^{1-\eta} (\sigma F)^{\frac{1-\eta}{1-\sigma}} \left(\frac{\sigma}{\sigma-1}\right)^{\eta-1}} X_{n,t} + \frac{E_t L_{i,t}^{\frac{1-\eta}{1-\sigma}} \left(\frac{d_{xi,t}w_{i,t}}{A_{i,t}}\right)^{1-\eta}}{\sum_{n\in N} L_{n,t}^{\frac{1-\eta}{1-\sigma}} \left(\frac{d_{xn,t}w_{n,t}}{A_{n,t}}\right)^{1-\eta}} \tag{14}$$

It is then possible to define a consumer market access term $CMA_{i,t} = P_{i,t}^{1-\eta}$ and a firm market access term $FMA_{i,t} = \sum_{n\in N} \frac{X_{n,t}}{P_{n,t}^{1-\eta}} d_{ni,t}^{1-\eta} + \frac{X_{x,t}}{P_{x,t}^{1-\eta}} d_{xi,t}^{1-\eta}$. Imposing the assumptions that trade costs are symmetric (i.e. $d_{ni,t} = d_{in,t}$) and that imports equal exports, we obtain the result that:

$$CMA_{i,t} = FMA_{i,t} = MA_{i,t} = \sum_{n\in N} \frac{d_{ni,t}^{1-\eta} X_{n,t}}{MA_{n,t}} + \frac{E_t d_{xi,t}^{1-\eta}}{\sum_{k\in N} d_{xk,t}^{1-\eta} \frac{X_{k,t}}{MA_{k,t}}} \tag{15}$$

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2.6 General equilibrium

The sequential equilibrium of the model is the set of labor units $\{L_{n,t}\}$, migration shares $\{m_{ni,t}\}$, wages $\{w_{n,t}\}$, market access terms $\{MA_{n,t}\}$ and expected lifetime utilities $\{V_{n,t}\}$, that solve the following system of equations for all locations $i, n \in N$ and all time periods t:

1. Each location's income equals expenditure on goods produced in that location:

$$w_{i,t}L_{i,t} = \frac{L_{i,t}^{\frac{1-\eta}{1-\sigma}} \left(\frac{w_{i,t}}{A_{i,t}}\right)^{1-\eta}}{(\sigma F)^{\frac{1-\eta}{1-\sigma}} \left(\frac{\sigma}{\sigma-1}\right)^{\eta-1}} MA_{i,t} \tag{16}$$

2. Market access is given by:

$$MA_{i,t} = \sum_{n\in N} \frac{d_{ni,t}^{1-\eta} w_{n,t} L_{n,t}}{MA_{n,t}} + \frac{E_t d_{xi,t}^{1-\eta}}{\sum_{k\in N} d_{xk,t}^{1-\eta} \frac{w_{k,t}L_{k,t}}{MA_{k,t}}} \tag{17}$$

3. Expected lifetime utilities satisfy:

$$V_{n,t} = \alpha ln w_{n,t} - \alpha ln P_{n,t} - (1-\alpha) ln \left(\frac{(1-\alpha)\, L_{n,t}}{H_{n,t}}\right) + \nu ln \sum_{i\in N} \left(exp\left[\beta V_{i,t+1} - \mu_{in} + B_{i,t}\right]\right)^{\frac{1}{\nu}} \tag{18}$$

4. Migration shares satisfy:

$$m_{in,t} = \frac{\left(exp\left[\beta V_{i,t+1} - \mu_{in} + B_{i,t}\right]\right)^{\frac{1}{\nu}}}{\sum_{k\in N} \left(exp\left[\beta V_{k,t+1} - \mu_{kn} + B_{k,t}\right]\right)^{\frac{1}{\nu}}} \tag{19}$$

5. The evolution of labor units is given by:

$$L_{n,t+1} = \sum_{i\in N} m_{ni,t} L_{i,t} \tag{20}$$

Following Caliendo et al. (2019), a stationary equilibrium of the model is a sequential equilibrium such that $\{L_{n,t}, m_{ni,t}, w_{n,t}, MA_{n,t}, V_{n,t}\}_{t=0}^{\infty}$ are constant for all t.

2.7 Aggregate welfare

Appendix D shows that the expected lifetime utility of residing in location n at time t is given by:

$$V_{n,t} = \sum_{s=t}^{\infty} \beta^{s-t} ln \left(\frac{w_{n,s}^{\alpha} exp\left(B_{n,s}\right)}{P_{n,s}^{\alpha} \left(\frac{(1-\alpha)L_{n,s}}{H_{n,s}}\right)^{1-\alpha} (m_{nn,s})^{\nu}} \right) \tag{21}$$

This welfare measure (and welfare changes induced by changes in fundamentals) may vary across locations. Welfare is aggregated across locations using a utilitarian approach which captures the mean welfare across all locations weighted by their respective initial population shares (following, for instance, Caliendo et al. (2019)):

$$W_t = \sum_{n \in N} \frac{L_{n,0}}{\sum_{i \in N} L_{i,0}} \left\{ \sum_{s=t}^{\infty} \beta^{s-t} ln \left(\frac{w_{n,s}^{\alpha} exp\left(B_{n,s}\right)}{P_{n,s}^{\alpha} \left(\frac{(1-\alpha)L_{n,s}}{H_{n,s}}\right)^{1-\alpha} m_{nn,s}^{\nu}} \right) \right\} \tag{22}$$

3 Data

The empirical analysis draws on geographic, demographic, economic and transport data at the level of Vietnam's secondary administrative divisions. In 2010, the country was divided into 697 secondary divisions (provincial cities, urban districts, towns and rural districts, hereafter 'districts') within 63 primary divisions (provinces and municipalities). I use 541 spatial units based on districts, aggregated where necessary to achieve consistent boundaries over the study period and ensure units can be separately identified in the economic data.[4]

3.1 Geographic data

I assign the location of each unit to the latitude and longitude of its centroid. Land areas without permanent ice and water are calculated from the Gridded Population of the World (GPW) version 4 dataset of the Center for International Earth Science Information Network (CIESIN) at Columbia University.

Digital elevation data is obtained from the NASA Shuttle Radar Topographic Mission dataset of the Consultative Group on International Agricultural Research's Consortium for Spatial Information. This data reveals the vulnerability of Vietnam's coastal districts to rising sea levels. Under a 1m sea level rise, 5% of Vietnam's land area and 38% of the Mekong River Delta would be inundated (GFDRR (2015), ICEM (2009)), with the country ranked among the top five countries globally likely to be affected by climate change. The LECZ is particularly susceptible to cyclones and flooding (as shown in Figure A1), which together accounted for 90% of natural disaster events and 94% of deaths from 1900-2015 (Guha-Sapir et al. (2015)).

3.2 Population data

The population of each spatial unit in 2010 is calculated using the GPW dataset, which uses district-level data from Vietnam's 2009 Population Census. Population data by district in 1999 is available for most districts from Miguel and Roland (2011), and extrapolated data is available for the remaining districts from GPW. In order to evaluate how well the model predicts dynamic changes in the spatial

[4]While most data are available at the district level, small area estimation is required to obtain expenditure per capita data at this level and some approximations are needed to assign an origin district to internal migrants within their province of origin (described below). To check that these factors are not driving the results, I also conduct the analysis at the province level (at which level all data are available in consistent boundaries for the entire study period) and obtain qualitatively similar results.

distribution of the population, 2015 and 2019 data on province-level populations is obtained from the General Statistics Office of Vietnam.[5]

As shown in Figure 2, Vietnam's population is strongly concentrated in the low elevation fertile flood plains of the Red River and Mekong River deltas and coastal harbors (Falvey (2010), Forbes (1996)). The country's sub-10m LECZ[6] is home to a strikingly large share of its population by global standards: in 2000, it contained the fourth largest population share (55%) and the ninth largest land share (20%) (McGranahan et al. (2007)). While historically important, the LECZ has been on a trajectory of decline in recent decades. The country has experienced drastic structural change following a wide-ranging series of economic reforms ('Doi Moi'[7]) beginning in 1986: from 1990 to 2008, the share of agriculture in GDP fell from 24% to 17% and in employment from 73% to 54% (McCaig and Pavcnik (2013)). This has been accompanied by a shift in the population distribution away from the coast and deltas towards less agrarian regions (as shown in Figure A2) and a commensurate 4 percentage point decline in the sub-5m LECZ's population share.

3.3 Economic data

The central measure of district-level economic activity in 2010 is expenditure per capita data from Lanjouw et al. (2013). This dataset uses small area estimation techniques combining data from the Vietnam Household Living Standards Survey (VHLSS, described at Appendix B.1) and population census. Miguel and Roland (2011) report similar estimates for 1999. The use of expenditure per capita data reflects the fact that consumption data are often preferred to income data in developing countries in light of evidence that the former may be more accurate and closely linked to permanent income (e.g. Ravallion (1994), Glewwe et al. (2002)). In robustness specifications, I instead use district-level wage data from the Vietnam Enterprise Census (VEC, described at Appendix B.1).

Consistent with the evidence of an inland shift in the locus of economic activity from population trends described in Section 3.2, the sub-5m LECZ also experienced slower wage growth from 2000 to 2010 using both of the measures described.[8]

At the province level, I use 2010 data published by the General Statistics Office of Vietnam on income from all sources (salary and wage activities; agriculture, forestry and fishery; non-agriculture, forestry and fishery; and other sources) to calibrate the model at the province level.

International exports data are taken from the General Statistics Office of Vietnam. I use the indicator 'export of goods' and convert 2000 values to constant 2010 values using a CPI deflator.

[5] This data is not available at the district level.

[6] The sub-10m LECZ is defined as the contiguous area along the coast that is less than 10m above sea level, consistent with the definition used by NASA's *Socioeconomic Data and Applications Center*.

[7] The 'Doi Moi' ('Renovation') program of economic reforms was a series of sweeping reforms to the cooperative system, household registration, industry and international integration that aimed to instigate a gradual shift from central planning towards a market-oriented economy.

[8] The formal sector wage increased by a population-weighted average of 97% in the sub-5m LECZ versus a country average of 118%. The corresponding increases for expenditure per capita were 177% and 183% respectively.

3.4 Migration data

IPUMS International provides data on internal migration from a 15% sample of the 2009 Population and Housing Census (IPUMS (2015)), including the respondent's current province and district of residence; whether they migrated within district, within province, across provinces or abroad within the last five years; and their province of residence five years ago. Following GSO (2011), I define an internal migrant as an individual aged five or older who lives in Vietnam and whose place of residence five years prior to the census was different from their current place of residence.[9] This data can be used directly to obtain internal migration flows at the province level. For district-level analysis, I assign an origin district for all internal migrants by assuming that internal migrants were distributed across districts in their reported province of origin in proportion to the districts' shares of the provincial population at the last census.

3.5 Transport cost data

I map Vietnam's road, inland waterway and coastal shipping networks in 2000 and 2010 using manually digitized data described at Appendix B.[10] Investment in the transport sector more than doubled between 2004 and 2009 to reach 4.5% of GDP, a high level by regional and international standards[11], with road spending of 3.6% of GDP dominating this (ADB (2012)). Figure 3 shows road maps of Vietnam at the beginning and end of the study period. While the total length of the road network increased by only 0.6%, there were significant upgrades of the existing network from secondary roads (minor and other roads) to main roads (freeways, dual carriageways and major roads). The spatial targeting of these upgrades is striking. Road upgrades were particularly pronounced in the sub-5m LECZ, where the length of main roads increased by 262% compared to an increase of 156% across the country as a whole. Even after controlling for land area and population, districts in the sub-5m LECZ received differential road improvements.

Appendix B describes the data used to assign to each stretch of the network in both years a direct economic cost of transportation per ton-km (to represent, for instance, fuel costs) and a travel time cost associated with time spent in transit. For each mode of transport used along a route, I also assign a one-off mobilization charge per ton (capturing, for example, loading and unloading) as such costs can have significant impacts on modal shares over different distances - for example, while travel costs per ton-km are lowest for coastal shipping, the extremely high mobilization costs are prohibitive for all but the longest journeys. All 2000 costs are converted to constant 2010 values

[9]International migrants are excluded from the analysis, consistent with the model's assumption of immobility of labor between countries (see Section 2). It is estimated that approximately 80,000 workers leave Vietnam each year (Ministry of Foreign Affairs of Vietnam (2012)); this represented approximately 0.1% of the total population in 2000 and 2010.

[10]In 2008, air transportation accounted for less than 1% of inter-provincial freight tons or ton-kms. Rail transport accounted for 2% and 4% of inter-provincial freight tons and ton-kms respectively and was not competitive over any haulage length during the study period (Blancas and El-Hifnawi (2013)), consistent with widespread evidence that the the quality and utilisation of Vietnam's railway network is low (e.g. Nogales (2004), ADB (2012)). To calculate bilateral transport costs, I therefore consider only road, inland waterway and coastal shipping routes.

[11]For example, transport infrastructure spending averaged approximately 1% of GDP in OECD countries in recent decades (OECD (2015)).

in the local currency (Vietnamese Dong) using a CPI deflator. Based on these networks, I use the Network Analyst extension in ArcGIS (which employs the Dijkstra algorithm) to compute the bilateral transport cost along the lowest cost route between any two points on the transport network in each year. Intra spatial unit travel costs are estimated as described at Appendix B.

The travel cost from each spatial unit centroid to international markets is calculated as the travel cost from the centroid to the nearest international port plus a fixed amount to account for the cost of shipping goods from an international port to foreign markets. To obtain the latter value, I use the estimate from Baum-Snow et al. (2018) that the cost of reaching foreign markets from international ports is approximately 15% of the average cost of reaching the port from interior locations.[12]

3.6 Road construction costs

I calculate the relative construction costs of realized and counterfactual road upgrades following the methods used in Faber (2014) and Alder (2019). These use a construction cost function based on the engineering literature, which gives relative road construction costs for area cells on different terrains:

$$Construction\ Cost = 1 + Slope + (25 \times Builtup) + (25 \times Water) + (25 \times Wetland) \tag{23}$$

I generate a 1km x 1km grid covering the entire surface of Vietnam and for each cell in the grid calculate the *Construction Cost* variable in Equation (23) as follows. I assign to each grid cell a value for the *Slope* variable equal to the mean slope within the cell. For each grid cell, I assign a value of 1 to the dummy variables *Builtup*, *Water* or *Wetland* where the majority of the cell is classified as having land type 'urban and built up', 'water' or 'permanent wetlands' respectively in land cover data obtained at a resolution of 15 arc-seconds from the US Geological Survey. Appendix B.3 uses geo-referenced data from 17 road construction projects across Vietnam from 2000 to 2010 with reported project costs to provide evidence that the relative grid cell level construction costs implied by this function fit reported construction costs well.

4 Model Parameterization and Calibration

This section describes parameterization of the model and uses these parameters together with the data described in Section 3 and the model's equilibrium conditions to calibrate district-level values for market access and relative productivities across districts in an initial period.

4.1 Parameterizing iceberg trade costs

The method described in Subsection 3.5 yields bilateral transport costs between each pair of spatial units, within each spatial unit, and between each spatial unit and international markets. I parameterize iceberg trade costs using 2009 data on inter-provincial trade flows from JICA (2010) and

[12]International ports comprise 26 international seaports (described at Appendix B.2.4), five international border connections of the Asian Highway Network (geo-referenced from ERIA (2010)) and Vietnam's three major international airports (obtained from https://www.naturalearthdata.com/).

measured transport costs between province pairs. For bilateral province pairs with positive trade, I model iceberg trade costs $d_{ni} = t_{ni}^{\phi} e_{ni}$ as a constant elasticity function of measured transport costs t_{ni} and a stochastic error e_{ni}.[13] Taking logarithms of the gravity equation (10) in a given time period yields:[14]

$$ln(\pi_{ni}) = \chi_i + \psi_n + \phi(1-\eta)ln(t_{ni}) + \varepsilon_{ni}$$

where the origin location fixed effect χ_i controls for population L_i, wages w_i and productivities A_i, while the destination location fixed effect ψ_n controls for the multilateral resistance term in the denominator of equation (10).

Estimating this equation for all province pairs with positive trade flows in 2009 yields a coefficient on log measured transport costs $ln(t_{ni})$ of $\phi(1-\eta) = -2.0$ with a regression R-squared of 0.5.[15] As an over-identification check, regressing log inter-provincial trade flows and measured transport costs on origin and destination fixed effects and plotting the resultant residuals yields an approximately linear relationship as shown in Figure A3, providing reassurance that the log linear functional form provides a good approximation.

To obtain the elasticity of iceberg trade costs with respect to measured transport costs ϕ from this estimate, a value is also needed for the CES parameter η. I use the method outlined in Kucheryavyy et al. (2016) together with data from Vietnam to estimate the trade elasticity $\eta - 1$ and hence obtain a value for the CES parameter η. Industry-level estimates of trade elasticities from Bartelme et al. (2018) are combined with 2010 industry trade shares in Vietnam from World Bank (2014) to obtain a trade share weighted average trade elasticity that implies $\eta = 7.92$. Based on this and the coefficient $\phi(1-\eta) = -2.0$ from estimation of the gravity equation, I use an elasticity of iceberg trade costs with respect to measured transport costs of $\phi = 0.3$.

The CES parameter σ is similarly obtained using the method outlined in Kucheryavyy et al. (2016). In this case, industry-level estimates of scale elasticities from Bartelme et al. (2018) are combined with 2010 industry trade shares in Vietnam from World Bank (2014) to obtain a trade share weighted average scale elasticity $\frac{1}{\sigma-1}$ that implies $\sigma = 10.55$.

4.2 Residential land share in consumption expenditure

While developed country estimates of the residential land share in consumption expenditure, $1-\alpha$, generally use rental payments data and imputed rents for owner-occupied housing (e.g. Davis and Ortalo-Magné (2011)), such estimates are difficult to obtain for Vietnam given thin rental markets and a low proportion of households reporting spending on rent in survey data. Kozel (2014) estimates consumption aggregates in Vietnam based on the 2004-2010 rounds of the VHLSS and finds that housing consumption represented 15%, 15%, 16% and 15% of total consumption in each survey.

[13] The model implies prohibitive trade costs for province pairs for which trade flows are zero.

[14] Other studies in the literature use a similar approach regressing log trade flows on log distance (e.g. Monte et al. (2018), Redding (2016)) - which will not be appropriate here given my interest in changes in transport infrastructure - or log travel time (Arkolakis et al. (2021)).

[15] A similar significant coefficient of -1.8 is obtained where measured transport costs between province pairs are instrumented using intra-province distance. Results are robust to instead parameterizing ϕ based on this estimate.

Based on this, I assume a residential land share in consumption expenditure of 15% and consequently set $\alpha = 0.85$.

4.3 Migration elasticity

Estimates of the migration elasticity $\frac{1}{\nu}$ are scarce, especially in developing countries, but generally lie in the range 2 to 4 (Morten and Oliveira (2014) in Brazil, Bryan and Morten (2018) in Indonesia and the USA, Tombe and Zhu (2019) in China[16]). I take 3 as my baseline value for $\frac{1}{\nu}$ and consider the robustness of results to values in the range 2 to 4 (see Table 2).

4.4 Discount factor

The discount factor β corresponds to a five-yearly discount factor, since the model is simulated at five-yearly intervals. The annual discount factor is a parameter widely used in the macroeconomic literature, with values generally between 0.89 and 0.99. Recent studies have highlighted arguments in favor of values at the higher end of this range given current near-zero real interest rates (Dhingra et al. (2017)) and in the context of climate change mitigation strategies (Stern (2007)). I present estimates using an annual discount factor of 0.96, common in much of the macroeconomics literature (which implies a five-yearly discount factor of 0.82) and in robustness specifications use an annual discount factor of 0.986, more in line with recent estimates and those used in the climate change literature (which implies a five-yearly discount factor of 0.93).

4.5 Calibrating district-level market access and productivities

The model can be used together with the data described in Section 3 to obtain the relative district-level market access and productivity values that are consistent with the observed data being an equilibrium outcome of the model in an initial period. Inverting equilibrium conditions (16) and (17) using data from 2010 yields calibrated values as shown in Figure 4. Reassuringly, calibrated market access values are highest for areas with dense road and waterway access and regions of high calibrated productivities coincide with Vietnam's 'Key Economic Zones' in the southeast, Hanoi-Haiphong corridor and central coast.

To conduct a more rigorous over-identification check of how well the calibrated relative district productivities correlate with other data on common measures of productivity, I use firm-level data from the VEC to estimate the average total factor productivity (TFP) of formal sector firms in each district. The data available for this analysis is not a panel, precluding TFP estimation based on methods commonly used in the firm productivity literature (e.g. Olley and Pakes (1996) or Levinsohn and Petrin (2003)). I instead construct simple TFP estimates using the available cross-sectional data on output, capital and labor inputs and calculate the mean value for each spatial unit

[16]Note that the latter two sets of estimates are based on idiosyncratic draws for worker productivity in each location rather than for worker preferences. However, Tombe and Zhu (2019) show that the welfare and real GDP effects of trade cost changes are identical under the two interpretations; the key difference is that the higher average draws contribute to output under the productivity interpretation but enter utility directly without affecting output under the preferences interpretation.

excluding 1% outliers. I consider specifications assuming either a Cobb-Douglas production function $Y_i = (TFP)_i K_i^{\frac{1}{3}} L_i^{\frac{2}{3}}$ or a production function that is linear in labor, $Y_i = (TFP)_i L_i$. The estimates are strongly positively correlated with the calibrated productivity values by spatial unit, as shown in Table 1.

5 Model Simulation and the Effects of Realized Road Upgrades

The motivating evidence from the data description in Section 3 suggests that, despite a shift inland in the locus of Vietnam's economic activity in recent decades and worsening coastal vulnerability, coastal regions have been a significant focus of major transport infrastructure investments.[17] In this Section, I describe how the data described in Section 3 is used to structurally estimate the model in Section 2 and quantify the returns to these investments with and without accounting for the projected effects of climate change. In Section 6 below, I then turn to the central results that use counterfactual simulations of the model to consider how far the returns that alternative transport infrastructure investments confer may be influenced by projected changes in the environmental vulnerability of coastal regions over the coming decades.

5.1 Simulating the baseline economy

The model is simulated forward at five year intervals to solve for the sequential equilibrium path of the endogenous variables $\{L_{n,t}, m_{ni,t}, w_{n,t}, MA_{n,t}\}_{t=0}^{\infty}$ in each location. This takes as given data on initial district-level populations $L_{n,2010}$, wages $w_{n,2010}$ and five year migration rates $m_{in,2005-2010}$ and aggregate international exports E_{2010}; an assumed time path of land areas $H_{n,t}$ and transport costs $d_{ni,t}$ and $d_{xn,t}$. The baseline simulations assume that relative district-level productivities A_i, amenities B_i, migration costs μ_{ni} and the real value of output in the rest of the world $\frac{X_x}{P_x^{1-\eta}} = \frac{E_{2010}}{\sum_{k \in N} d_{xk,2010}^{1-\eta} \frac{w_{k,2010} L_{k,2010}}{MA_{k,2010}}}$ remain constant over time.

Following Caliendo et al. (2019), an iterative solution algorithm is used which solves equilibrium conditions (16), (17) and (20) together with the remaining equilibrium conditions in relative time differences (A14) and (A15) (derived at Appendix D). This solution method requires the assumption that, over time, the economy approaches a stationary equilibrium in which aggregate variables are constant over time. The central estimates assume that the economy reaches a stationary equilibrium in 250 years; the robustness of the results to altering this assumption is considered in Section 6.4.

Another evaluation of the model's performance can be conducted by assessing how well dynamic changes in the spatial distribution of economic activity predicted by the model match those observed in the data. While post-2010 data on the evolution of the model's endogenous variables is not available at the district level, province-level population data is available for 2015 and 2019. I use this data to compare province-level population share changes predicted by the model from 2010-2015 and 2015-2020 to those observed in the data from 2010-2015 and 2015-2019 respectively (where the

[17]Other evidence suggests that Vietnam's development strategy more broadly continues to favor the growth of urban areas in coastal and low-lying regions (DiGregorio (2013)).

latter are not used in the estimation). As shown in Figure 5, the model matches the data well: for both the 2010-2015 and 2015-2020 simulation periods, observations are close to the 45° line, with an R^2 of 0.25 and 0.58 respectively.[18]

5.2 Modeling future sea level rise

There is considerable variation in global sea level rise projections. While more extreme estimates project rises up to 5 meters over the next century (Dasgupta et al. (2009)), most estimates lie in the range 0.2 to 2 meters by 2100 (Melillo et al. (2014)), with emerging data suggesting that scenarios at the higher end of this range are more likely.[19] I use a central scenario of a gradual rise reaching 1 meter by 2110, which represents a best estimate of sea level rise over this period based on current projections as summarized in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (Qin et al. (2014)).[20]

In simulations of the model incorporating future sea level rise, this is manifested in two ways. First, inundated areas will see a gradual decline in their available land area $H_{n,t}$. I calculate the proportion of each district's land area below 1 meter and reduce its available land area by this amount in equal increments each period from 2010 to 2110. Second, inundated areas will experience increases in their trade cost matrices $d_{ni,t}$ and $d_{xi,t}$ as inundated stretches of the road network become more costly to traverse. I assume that the per-kilometer cost of traversing a stretch of inundated road is double the per-kilometer cost of traversing the most costly road type in 2010.[21] In simulations incorporating future sea level rise, I incrementally increase travel costs on all stretches of road that lie below 1 meter elevation such that they are entirely inundated by 2110. In the baseline estimates, I assume that agents are perfectly foresighted about these changes, and in Section 6.4 consider robustness to instead assuming myopic agents for whom sea level rise arrives as an unanticipated shock.

5.3 Estimating the effects of realized road upgrades

I quantify the dynamic welfare gains from the realized road upgrades made in Vietnam between 2000 and 2010 by simulating the effects of their removal. To achieve this, I re-simulate the model using trade cost matrices d_{ni} and d_{xi} that reflect the transport network that would have existed had there been no road upgrades made from 2000 to 2010. To isolate the effect of road upgrades

[18] This comparison is conducted for the central case with a 1 meter rise in the sea level realized gradually over the next 100 years. Similar results are obtained in the case with no inundation: observations remain close to the 45° line, with an R^2 of 0.23 and 0.55 respectively.

[19] See, for example, https://sealevel.nasa.gov/understanding-sea-level/projections/empirical-projections.

[20] Current projections suggest that accelerating sea level rise will continue further into the future than 100 years. Given the uncertainty of projections for both climate changes and adaptation measures so far into the future - and in the interest of conservative estimation - I exclude further sea level rise beyond 2110 from the simulations.

[21] Common approaches to modeling the disruptive impact of flooding on road transportation assuming a road is fully operational or fully blocked have been recognized as inconsistent with empirical evidence (Pregnolato et al. (2017)). While it is challenging to model the cost of travel over an inundated road and the effects of gradually rising sea levels may differ from those due to idiosyncratic flood events, the assumption here (which represents a 360% increase in the per-kilometer cost of traversing a stretch of road with the mean pre-inundation cost) is consistent with evidence on travel time increases due to flooding in empirical studies (e.g. Pyatkova et al. (2019)).

alone, seaport proliferation and capacity upgrades between 2000 and 2010 are incorporated in the counterfactual simulation excluding the realized road upgrades, as are changes in mobilization costs, direct transport costs per kilometer and travel speeds on each mode.[22]

The change in welfare induced by this change in the economy's fundamentals can be derived from Equation (21). Denoting by $\widehat{x}$ the value of a variable under the realized upgrades and x the value under the alternative scenario with no upgrades, the aggregate welfare change (derived at Appendix D) is given by:

$$\triangle Welfare_t = \sum_{n\in N} \frac{L_{n,0}}{\sum_{i\in N} L_{i,0}} \left\{ (1-\beta) \sum_{s=t}^{\infty} \beta^{s-t} ln \left(\frac{\left(\frac{\widehat{w_{n,s}}}{w_{n,s}}\right)^{\alpha} \frac{exp\left(\widehat{B_{n,s}}\right)}{exp(B_{n,s})}}{\left(\frac{\widehat{P_{n,s}}}{P_{n,s}}\right)^{\alpha} \left(\frac{\widehat{L_{n,s}}/L_{n,s}}{\widehat{H_{n,s}}/H_{n,s}}\right)^{1-\alpha} \left(\frac{\widehat{m_{nn,s}}}{m_{nn,s}}\right)^{\nu}} \right) \right\} \tag{24}$$

The results suggest that, in the central scenario with a gradual 1 meter rise in the sea level over 100 years, the net present value of aggregate welfare is 1.37% higher as a result of the realized road upgrades made from 2000 to 2010 than it would have been in the absence of any road upgrading over this period. Accounting for the effects of future sea level rise reduces the projected gains relative to simulations that exclude future inundation, which yield estimated welfare gains from the realized road investments of 1.56%. The fact that allowing for future sea level rise reduces the estimated welfare gains from road upgrading by 12% reflects the fact that a large share of upgraded roads are gradually lost to inundation, or connect inundated areas. As such, there are welfare costs associated with road investments that are lost to inundation and the tendency for the coastally-concentrated road investments to reinforce the concentration of the population in the low elevation coastal zone.

These results suggest that incorporating the future effects of inundation has an important impact on the estimated returns to transport infrastructure investments made today. While a large literature estimates the returns to transport upgrading projects in a range of contexts (e.g. Allen and Arkolakis (2014), Alder (2019), Baum-Snow et al. (2018)), the results of this analysis suggest that accounting for future climatic changes may substantially alter such estimates in environmentally vulnerable regions. These findings are also pertinent to the literature on optimal transport network design (Allen and Arkolakis (2019), Fajgelbaum and Schaal (2020)) in the context of a changing climate. In particular, considering the dynamic implications of future climate change may have important implications for designing infrastructure improvements. I turn to this in the next Section.

6 Climate Change and the Returns to Transport Investments

The results of the previous Section highlight that future sea level rise might alter the returns to infrastructure investments in important ways. When considering where to allocate infrastructure, this raises a question as to whether there may be welfare gains from pre-emptively directing investments inland in order to protect them from inundation and encourage economic activity to move away from

[22]As described in Appendix B, I obtain data on seaport locations and capacity, as well as mobilization costs, direct transport costs per kilometer and travel speeds by mode, in 2000 as well as 2010.

at-risk areas. In order to investigate this, I simulate the impacts of counterfactual allocation rules of the same total investment amount as the status quo investments that were made between 2000 and 2010, but which anticipate future sea level rise to varying degrees. The simulation method and calculation of implied welfare gains follow the method described in Section 5.3, where $\widehat{x}$ in Equation 24 now represents the value of a variable x under the relevant counterfactual.

6.1 Counterfactual allocations

The counterfactual simulations aim to shed light on the importance of future sea level rise in influencing the returns to transport investment decisions. As such, I focus attention on objective counterfactual allocation rules that approximate an efficient network in a computationally feasible manner and are comparable except for the extent to which they reflect future inundation risks.

The basis of these allocation rules is an objective to maximize pairwise market access, defined between a pair of districts i and j as $MA_{ij} = \left[\frac{w_i L_i}{MA_i} + \frac{w_j L_j}{MA_j}\right] d_{ij}^{1-\eta}$ and between a district i and international markets x as $MA_{ix} = \left[\frac{w_i L_i}{MA_i} + \frac{X_x}{P_x^{1-\eta}}\right] d_{ix}^{1-\eta}$ based on district-level data in 2000. While my setup does not lend itself to the application of recent advances in identifying optimal networks in particular classes of static general equilibrium spatial models (Fajgelbaum and Schaal (2020))[23], market access is commonly used in economic geography frameworks to provide a model-consistent metric capturing the importance of trade cost-weighted economic activity (Overman et al. (2003), Redding and Rossi-Hansberg (2017)), an important determinant of the returns to infrastructure investments (see, for example, Santamaria (2020)). As such, this approach provides a sensible basis for approximating an efficient network in a computationally feasible manner which permits a comparison between transport improvements that are comparable other than in their climate vulnerability. All counterfactuals considered have the same total cost as the status quo upgrades as determined by the road construction cost equation at equation (23).

The first counterfactual aims to maximize market access in a scenario which ignores the dynamic implications of future sea level rise. To construct this counterfactual, I rank spatial unit pairs and spatial unit - international market pairs according to their pairwise market access in 2000, use ArcGIS to find the quickest route between each of these pairs[24], and allocate one category road upgrades to these bilateral connections in order of the pairwise market access ranking until the same total investment in road upgrades as under the status quo has been allocated. The implied road network is shown in the first panel of Figure 6. As is evident from the figure, this scenario implies some concentration of upgrades in the LECZ - in line with its concentration of existing economic

[23]The model studied in Fajgelbaum and Schaal (2020) incorporates congestion in transport and a continuous infrastructure investment choice, which yields a convex optimization problem permitting computation of the globally optimal network. In the absence of these features, the model I use is not amenable to such approaches to identifying globally optimal network investments. In non-convex cases, heuristic algorithms have been applied to balance gains against construction costs using iterative removals and additions of links in the network (e.g. Alder (2019)) to approximate (locally) optimal networks, though such approaches may not obtain the global optimum and the extension to a dynamic context in my model renders such approaches prohibitively computationally intensive.

[24]In the case, of spatial unit - international market pairs, this is represented by the quickest route from the spatial unit to the nearest international port.

activity, on which the market access measure is based - but is less strongly concentrated in the LECZ than the status quo allocation.

The central contribution of the counterfactual analysis is to examine the importance of dynamic environmental considerations in designing infrastructure improvements. To investigate this, I consider a series of 'foresighted' counterfactuals which aim to anticipate future sea level rise by maximizing market access while avoiding the most vulnerable low-lying areas. As previously, I rank spatial unit pairs and spatial unit - international market pairs according to their 2000 pairwise market access, but in this case exclude connections for those districts that have a sufficiently high share of their land area below 1 meter. I consider three thresholds for this share: districts with more than 50% of their land area below 1 meter (excludes 20 districts), districts with more than 40% of their land area below 1 meter (excludes 42 districts) and districts with more than a third of their land area below 1 meter (excludes 66 districts). For the remaining connections, I find the quickest route between each of these pairs and allocate one category road upgrades to these bilateral connections in order of the pairwise market access ranking until the same total investment in road upgrades as under the status quo has been allocated.

The implied road networks are shown in the second, third and fourth panels of Figure 6. Intuitively, the maps in this figure demonstrate a decreasing degree of coastal concentration as a larger and larger number of coastal districts are excluded from the allocation of upgrades to their connections. The share of upgraded road length at less than 1 meter elevation is 6.3%, 5.4%, 5.1% and 3.8% respectively for the unconstrained market access maximizing counterfactual and the market access maximizing counterfactuals excluding connections to districts with more than 50%, 40% and a third of their land area below 1 meter respectively. All of these are significantly below the 11% share of road upgrade length that lies below 1m elevation for the status quo investments that were made between 2000 and 2010.

6.2 Counterfactual simulation results

The counterfactual simulation results reveal that accounting for future sea level rise meaningfully changes our assessment of where infrastructure should be allocated today.

The estimates suggest that forward-looking investment allocations achieve significantly higher gains under central sea level rise scenarios than those that do not take into account future inundation risks. Figure 7 shows welfare gains in the central scenario with a 1 meter rise in the sea level realized gradually over 100 years. While all counterfactuals outperform the status quo, the market access maximizing counterfactuals that are constrained to avoid vulnerable regions achieve higher aggregate welfare gains than the unconstrained market access maximizing counterfactual.[25] The counterfactuals maximizing market access excluding districts with more than 40% and 33% of their land area below 1 meter achieve substantial welfare improvements of 9% and 7% respectively relative to the unconstrained allocation.

[25] In the case of the counterfactual maximizing market access excluding the 20 districts with more than 50% of their land area below 1 meter, the implied road network is extremely similar and yields welfare gains that differ by less than 0.1%.

These estimates therefore suggest that, accounting for future inundation, there are welfare gains to be achieved by avoiding the most vulnerable regions. As a greater area is excluded from upgrades, the gains from excluding additional regions are eventually eroded due to foregoing the short-term gains from connecting densely populated coastal areas. These simulations suggest that the relative gains from avoiding upgrades in vulnerable regions increase up to the point at which districts with more than 40% of their land area below 1 meter are excluded, but begin to decline thereafter.

The second key implication of the simulation results is that failing to account for future climate changes would lead planners to conclude erroneously that higher welfare gains could be achieved by allocations that are not constrained to avoid the most vulnerable regions. Figure 8 considers results without accounting for future sea level rise and displays the relative welfare gains obtained under each counterfactual, as well as the status quo, in this case. These results demonstrate that unconstrained market access maximization yields the highest gains, an intuitive result since the constraint to avoid low elevation regions is irrelevant in the absence of sea level rise. In this case the counterfactuals excluding districts with more than 40% and 33% of their land area below 1 meter achieve welfare gains 21% and 24% *lower* respectively than the unconstrained market maximizing allocation.[26]

These differences highlight the importance of accounting for dynamic climate changes in considering infrastructure improvements. The finding that realized road upgrades were not optimal - consistent with the existing literature in other contexts (Fajgelbaum and Schaal (2020), Graff (2019)) - is robust both with and without accounting for the impacts of future inundation. Strikingly higher returns would in both cases have been available from all of the counterfactual allocations. Given that each of the counterfactuals is significantly less coastally concentrated than the status quo, as described in Section 6.1, the results suggest that the realized upgrades over-invested in coastal areas.[27] Importantly, however, climate change has significant implications for the pattern of gains from infrastructure investments and accentuates the welfare benefits from avoiding vulnerable regions. Accounting for future sea level rise renders coastally concentrated counterfactuals less valuable, while conversely the returns to foresighted counterfactuals avoiding vulnerable regions increase. As such, the implied inefficiency of the realized upgrades is much more pronounced once the effects of climate change are considered, and accounting for these changes has important implications for where infrastructure should be allocated to maximize welfare. These results highlight that consideration of future environmental change is central to assessing the returns to, and selecting the efficient allocation of, investments made today.

[26] The counterfactual maximizing market access excluding districts with more than 50% of their land area below 1 meter is again extremely similar.

[27] The literature has examined several reasons that infrastructure investments may not be allocated optimally (see, for instance, Burgess et al. (2015), Glaeser (2010), Do et al. (2017)). A separate literature considers particular inefficiencies that may be expected to contribute to over-investment in coastal regions, such as myopia or limited information regarding environmental risks (Kunreuther (1996)); moral hazard induced by post-disaster assistance (Kydland and Prescott (2004)); and a 'safe development paradox' whereby disaster management policies facilitate development in hazardous areas by inducing a false sense of security (Burby (2006)). The finding that there is over-investment in coastal areas is consistent with allocation decisions failing to keep pace with a reversal in coastal fortunes, contributing to path dependence (Krugman (1991a), Bleakley and Lin (2012)), and the related literature on policy myopia (see Section 6.3).

6.3 Dynamic considerations

The results in the previous subsection suggest that, once future sea level rise is accounted for, higher welfare gains accrue to counterfactual road investments that avoid vulnerable regions relative to comparable allocations that do not avoid these areas. This assessment rests on a dynamic tradeoff between the short-term costs of foregoing market access improvements in densely populated coastal areas versus the longer term gains from reducing exposure to inundation. The unconstrained market access maximizing allocation includes connections in coastal areas that are currently home to a large share of economic activity and therefore may be expected to garner the highest returns in the short-run. Given these regions' susceptibility to future sea level rise, however, a particularly high share of activity is exposed to inundation under this allocation as coastal inundation proceeds. The returns to foresighted allocations avoiding the most vulnerable regions therefore start to dominate over time once the longer term gains from lower exposure to inundation are considered.

Figure 9 considers this dynamic tradeoff in the scenario with a 1 meter rise in the sea level over 100 years, for the unconstrained market access maximizing counterfactual and the comparable foresighted counterfactual constrained to avoid upgrading connections to districts with more than 40% of their land area at less than 1 meter elevation. In the first five-year period of the simulation, the welfare gain from the unconstrained market access maximizing allocation (0.41%) exceeds that from the foresighted counterfactual (0.32%). As the time horizon over which welfare gains are aggregated is extended, however, the net present value of aggregate welfare gains increases more rapidly for the latter. Once the time horizon extends to 2055, the net present value of aggregate welfare gains is greater for the foresighted allocation avoiding the most vulnerable regions (1.89%) than for the unconstrained market access maximizing allocation (1.88%). Over the infinite horizon, the relative gains converge to 2.34% and 2.14% respectively in line with Figure 7.

These relative dynamic trajectories highlight that, while higher aggregate long-run welfare gains are available from foresighted allocations avoiding the most vulnerable regions, this comes at the expense of the short-run costs of foregoing upgrades in densely-populated coastal regions in the near term. This points to a potentially important role for policy myopia (Nordhaus (1975), Rogoff (1990), Rodrik (1996)) in driving dynamically sub-optimal infrastructure placement, if policymakers face short electoral time horizons. As such, consideration of the contemporaneous impacts of investments may dominate that of their long-term place-making effects even if the latter has an important bearing on optimal placement.

Critical to the tradeoff examined here is the choice of discount factor. As discussed in Section 5, the annual discount factor of 0.96 used in the central estimates is used commonly in the macroeconomics literature but likely conservative in this context. Table 2 presents results using an annual discount factor of 0.986 in line with more recent studies and the climate change literature. The results in this case display the same pattern as in the central estimates but with more pronounced magnitudes: in the scenario with sea level rise, the counterfactual excluding districts with more than 40% of their land area below 1 meter achieves welfare gains 41% higher than the unconstrained market access maximizing allocation (relative to 9% higher in the central estimates with an annual discount factor of 0.96). The dynamic trajectory in this case, shown in Appendix Figure A4, demonstrates that the welfare gains from the foresighted allocation exceed those from the unconstrained allocation once the time horizon considered reaches 2045. As Table 2 also shows, an annual discount factor of 0.94 is required to (approximately) equalize the aggregate welfare gain from the foresighted and unconstrained allocations.

6.4 Robustness tests

The results in the previous subsection suggest that accounting for future sea level rise is important in evaluating the returns to transport infrastructure investments, and that under central sea level rise scenarios the highest gains are achieved by allocations avoiding the most vulnerable coastal regions. These findings may be sensitive to assumptions about the trajectory of locational fundamentals, agents' preferences and information, and may be subject to the Lucas Critique if policy interventions also influence locational characteristics that the model assumes are constant (Redding and Rossi-Hansberg (2017)). This section tests the robustness of the results to varying these assumptions.[28]

Wider impacts of climate change on coastal productivities

The central estimates assume that productivities remain constant in coastal areas as sea level rise progresses. This may yield conservative estimates if climate change will have additional detrimental effects in coastal areas such as declines in agricultural and aquaculture productivity induced by saltwater intrusion, damages from more intense tropical cyclones or reduced attractiveness of coastal regions for tourism (IPCC (2001)). While subject to considerable uncertainty, some projections of such effects have been estimated in this and other contexts (e.g. Trieu and Phong (2015), Genua-Olmedo et al. (2016)). In line with these estimates, I re-simulate results when districts with more than 40% of their land area below 1 meter experience a gradual decline in productivity such that by 2110 their productivity levels have fallen by 15% relative to 2010. As shown in Table 2, this yields very similar results to the baseline estimates.

Secular trends in district-level productivities

Even notwithstanding the impacts of climate change, it is challenging to predict how regional productivities will evolve in the future. One guide may be recent secular trends such as structural change or increasing tourism. Table 2 presents the results of re-running all simulations assuming that trends in calibrated relative productivities across districts that were observed over 2000-2010 continue over the subsequent decade, with productivities linearly interpolated for the five-year interval in between. In this case, the central finding that the unconstrained market access maximizing allocation offers the highest returns if the effects of future sea level rise are ignored but the allocation

[28] Given the extremely close similarity between the counterfactuals maximizing market access and maximizing market access excluding districts with more than 50% of their land area below 1 meter, the latter are excluded from the reported results.

constrained to avoid low-lying regions affords the highest returns once sea level rise is accounted for, remains robust.

Increasing coastal amenity premium

Although hazard-prone, coastal areas also confer amenities such as sea views and recreation opportunities, which are reflected in a 'coastal premium' for residential housing prices (Benson et al. (1998), Fraser and Spencer (1998)). While the baseline estimates account for *fixed* differences in amenity values across locations, an increase in the amenity value attached to coastal proximity as development proceeds may favor road allocations concentrated nearer coasts. To test this, I assume that all 193 districts with land area within 10km of Vietnam's sea coast experience an increase in local amenities over time, while these remain constant in other districts.[29] I assume that amenity values in these districts currently reflect no coastal premium, and that in 100 years' time their amenity value will be 22% higher as the coastal premium reaches developed country levels, increasing in equal increments each period in the interim. This reflects a central estimate of the coastal premium of 50% from the literature applied to the 44% of the land area of the 193 coastal districts that lies within 10km of the coast. The results, shown in Table 2, are consistent with the patterns in the central estimates.

Increasing real value of output in the rest of the world

Another quantity which we might expect to undergo secular change over the simulation period is the real value of output in the rest of the world, held constant in the central estimates. Table 2 reports similar results assuming that the real value of output in the rest of the world increases in each year over the subsequent decade in line with the average annual growth rate of real world GDP over the preceding five years 2005-2010 obtained from the IMF Datamapper.

Unanticipated sea level rise

The baseline results assume that agents are perfectly foresighted about the evolution of the economy's fundamentals, including changes induced by future sea level rise. I consider the robustness of the results to instead assuming that agents are myopic about the effects of sea level rise in the future. I assume that agents expect that sea level rise will occur in line with climate projections 50 years into the future but that continuing sea level rise arrives as an unanticipated shock thereafter. This could reflect, for instance, an expectation of future mitigation measures or skepticism regarding longer-range climate projections. The solution algorithm in this case is described at Appendix C. Table 2 shows that, consistent with the central results with anticipated sea level rise, the realized road investments experience the sharpest decline in returns and the highest returns are achieved by foresighted counterfactual allocations avoiding vulnerable coastal regions.

[29]This reflects evidence that the premium is highly localized and disappears approximately 10km inland from the coast (Conroy and Milosch (2011)).

Depreciation of road investments

The central simulations consider the effects of the major ten-year road upgrade program undertaken in Vietnam between 2000 and 2010, and examine how these play out in a dynamic setting assuming that the Government maintains existing roads equally across space thereafter. This seems a sensible central assumption given that the location of existing roads is likely to be self-reinforcing as people and firms agglomerate nearby and that road maintenance is cheaper than new road construction. The Government may, however, alter the spatial distribution of road maintenance and upgrading in future periods, including to reduce climate exposure as inundation takes effect. The results in Table 2 consider cases where the time frame for the Government's investments from 2000-2010 are only 100 or 30 years by allowing the investments to depreciate fully over these time frames. The central results are robust to the first of these assumptions, while extreme assumptions about the short-term nature of investments - for instance that the Government only intended the road investments to be usable for 30 years - are needed for the unconstrained market access maximizing allocation to outperform the foresighted allocations avoiding the LECZ in the case with inundation.

Using formal sector wage data

As outlined in Section 3.3, two sources of wage data are available for each spatial unit used in the analysis. Qualitatively similar results are obtained using data on the formal-sector wage from the VEC instead of expenditure per capita data based on data from the VHLSS and population census, as shown in Table 2.

Timing of stationary equilibrium

As discussed in Section 5, the model solution requires that the economy approaches a stationary equilibrium in which aggregate variables do not change over time. The central estimates assume that the economy reaches a stationary equilibrium in 250 years. The results are almost identical to the central estimates when the model is re-simulated assuming that the stationary equilibrium is instead reached in 200 and 400 years.

7 Conclusions

Transport infrastructure investments attract huge levels of investment globally and this trend is set to intensify as developing countries invest in expansion and upgrading of their infrastructure networks. The burgeoning literature on the role of transport infrastructure in determining the spatial pattern of development finds sizable effects on the distribution of economic activity and welfare. It is therefore important to consider the placement of these investments carefully. This paper builds on this literature by examining the effects of environmental change which, as I show, fundamentally affects the gains from transport infrastructure investments.

I develop a dynamic spatial model which, combined with detailed micro-data in an illustrative country, allows me to quantify the significant gains that will be unrealized if infrastructure investments are not moved away from areas vulnerable to environmental change. The global climate is changing in a measurable way, with an estimated 56 million people living in areas of developing countries susceptible to inundation over the next century (Dasgupta et al. (2009)). I find that consideration of these changes is central to assessing the returns to, and selecting the efficient allocation of, investments made today. The results suggest that, in the presence of future environmental changes, the welfare gains from avoiding vulnerable areas are large. This highlights the importance of advancing a literature that connects environmental change to the location of economic production.

The set of issues considered in this paper are by no means only relevant in developing countries. Indeed all countries with large population concentrations in coastal regions are increasingly cognizant of the fact that the pattern of infrastructure investment may need to change dramatically from what may have been advisable based on the economic geography even a few decades ago. The methodologies developed in this paper could be applied to a range of contexts where authorities are rethinking the allocation of infrastructure investments across space. Developing countries require special focus, however, both because these economies are likely less able to afford the resources to protect their coastal populations from future inundation, and given that developing countries will be responsible for the majority of infrastructure investments in the coming decades. It may therefore be even more pressing for infrastructure allocations in these contexts to take into consideration the costs this paper has identified. Changing thinking towards placing infrastructure in locations which will generate the highest future returns, allowing for the effects of future environmental change, will be an important factor in determining the extent to which Governments keep populations out of harm's way and the level of development they can achieve.

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Tables and Figures

Figure 1: Road investments in Vietnam, 2000-2010

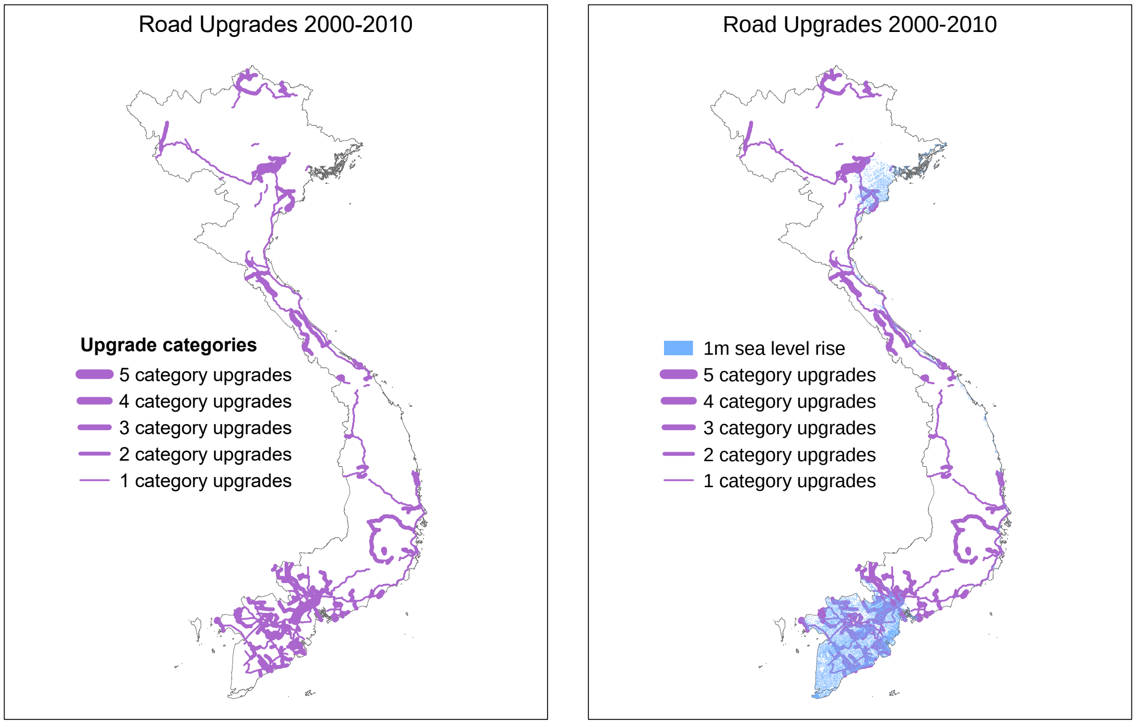


Figure 2: 2000 population density, elevation and major socioeconomic regions of Vietnam

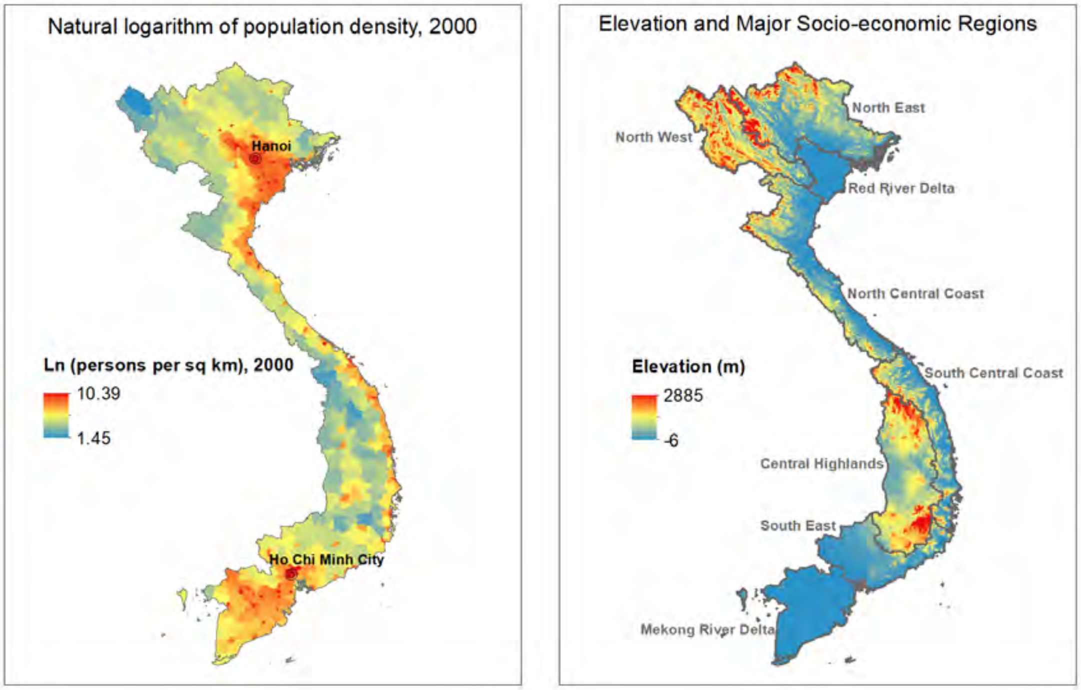


Figure 3: Road maps of Vietnam, 2000 and 2010

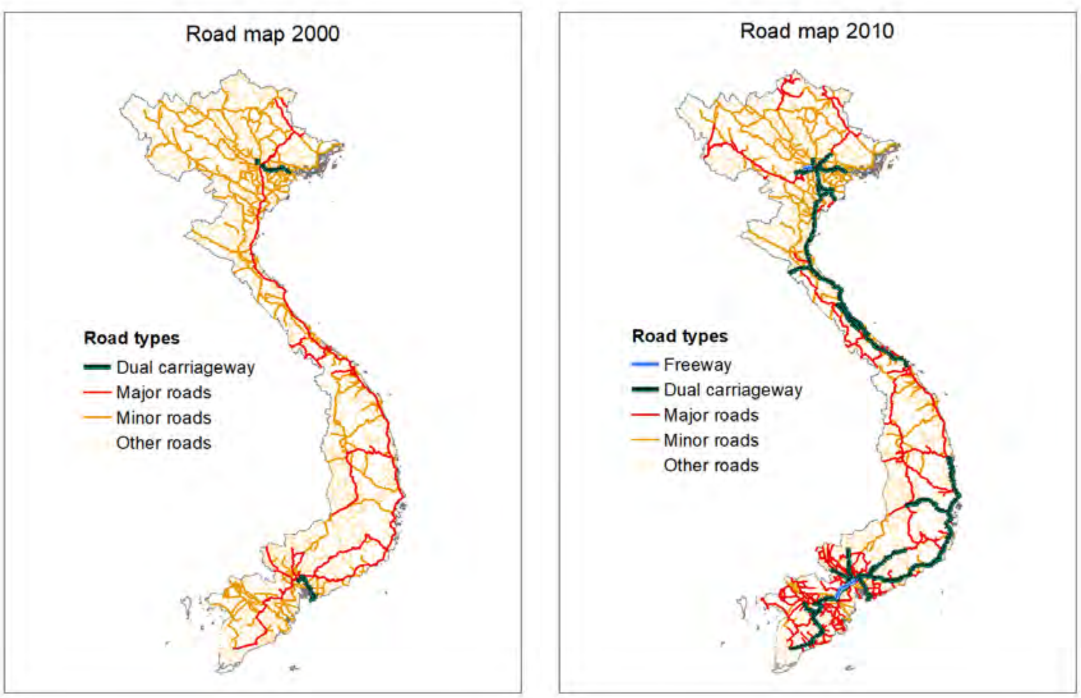
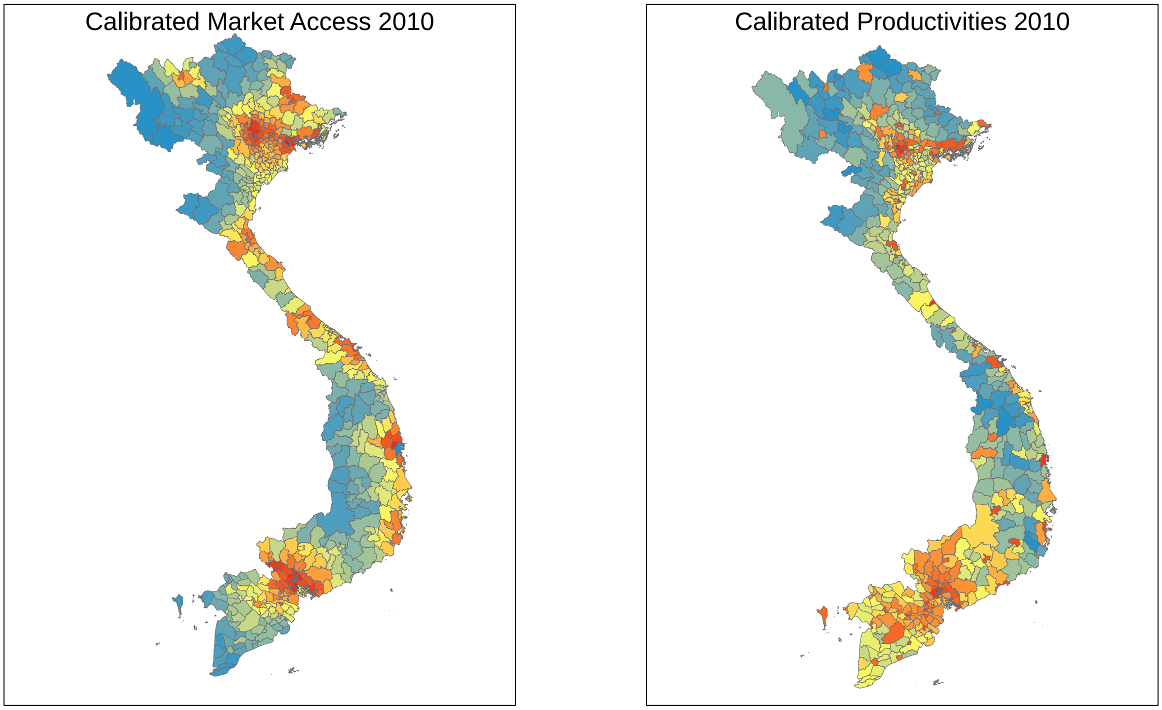


Figure 4: Calibrated market access and productivities in 2010



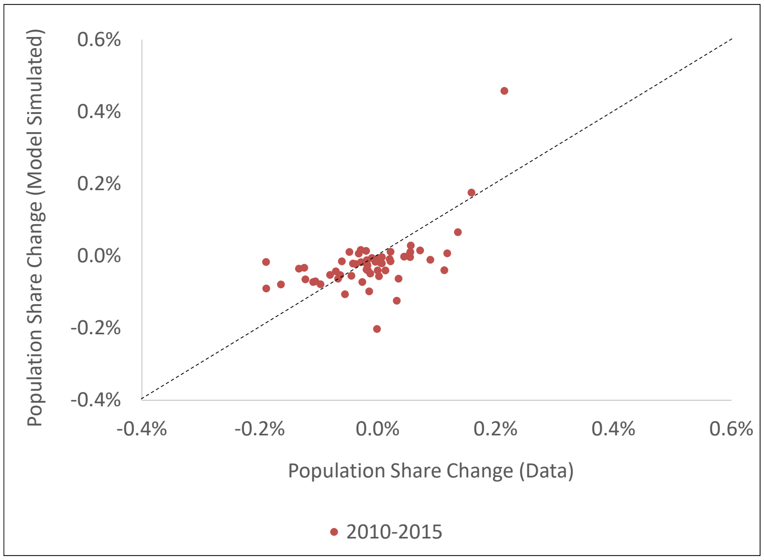
Notes: Data are reported at the level of district-based spatial units. Red (blue) units indicate higher (lower) values.

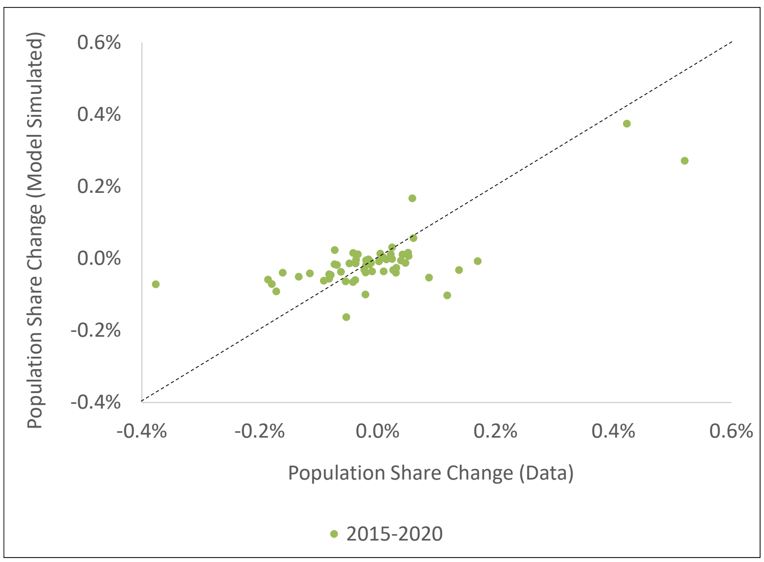
Table 1: Correlation between calibrated productivities and TFP in 2010

Dependent variable: Calibrated relative productivity level by district		
TFP estimated using $Y = AK^{\frac{1}{3}}L^{\frac{2}{3}}$	0.00886***	
	(0.00102)	
TFP estimated using $Y = AL$		0.00407***
		(0.000467)
Observations	540	540
R-squared	0.123	0.124

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

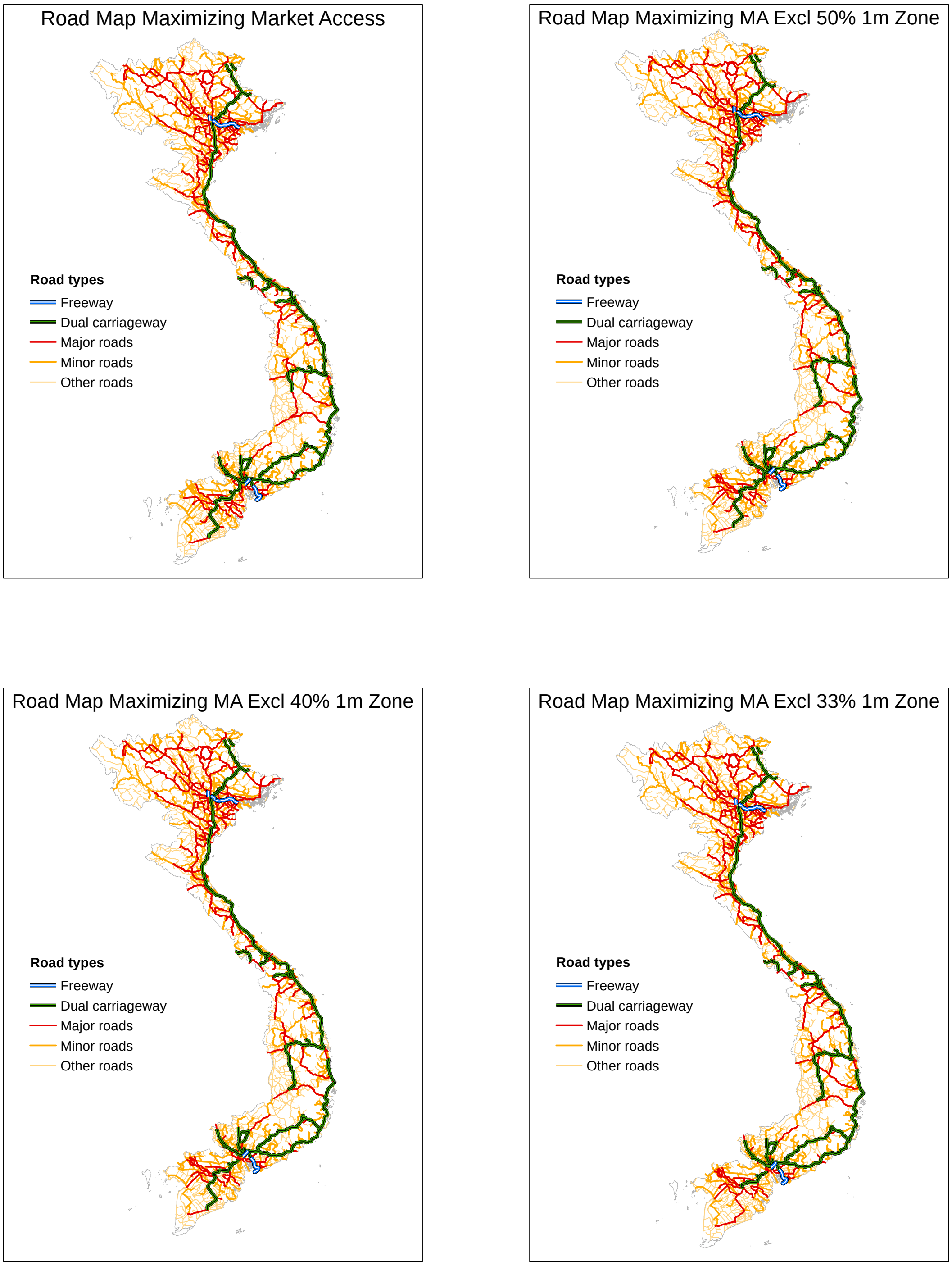
Figure 5: Population share change by province in model versus data





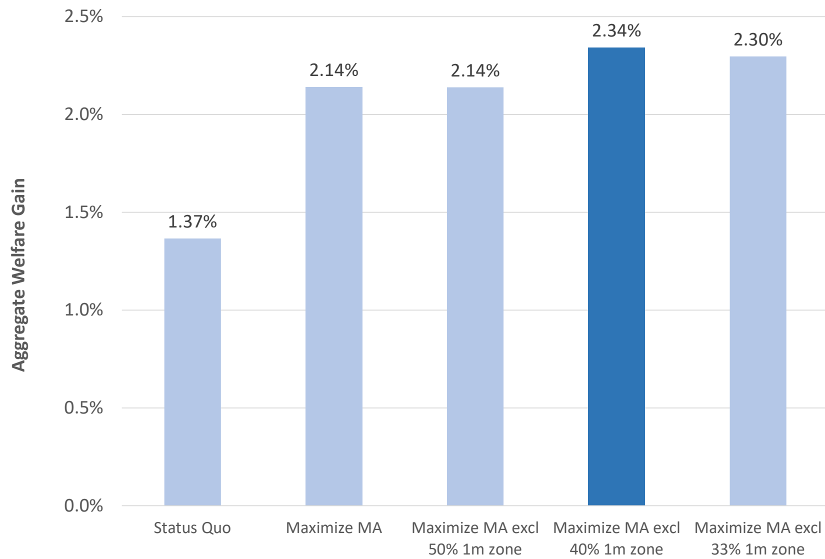
Notes: Dashed lines denote 45° line. The linear trendline has equation $y = 0.65x + 4 \times (10^{-18})$ *and* $R^2 = 0.25$ *for 2010-2015, and equation* $y = 0.67x - 1 \times (10^{-17})$ *and* $R^2 = 0.58$ *for 2015-2020.*

Figure 6: Counterfactual road networks



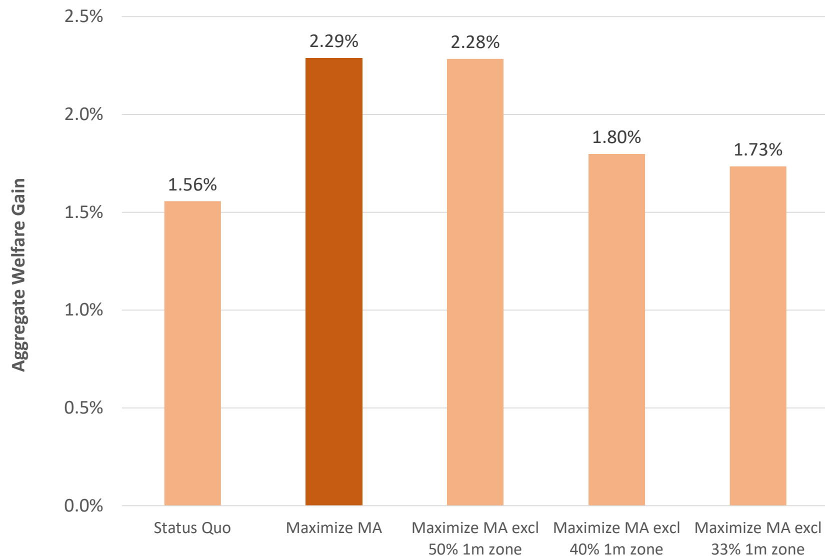
Notes: Counterfactual 'maximizing market access' maximizes pairwise market access between districts. Counterfactuals 'maximizing market access excluding 40% (33%) 1m zone' maximize pairwise market access excluding connections for districts with more than 40% (33%) of their land area below 1 meter.

Figure 7: Welfare gains from counterfactual road investments with 1m sea level rise over 100 years



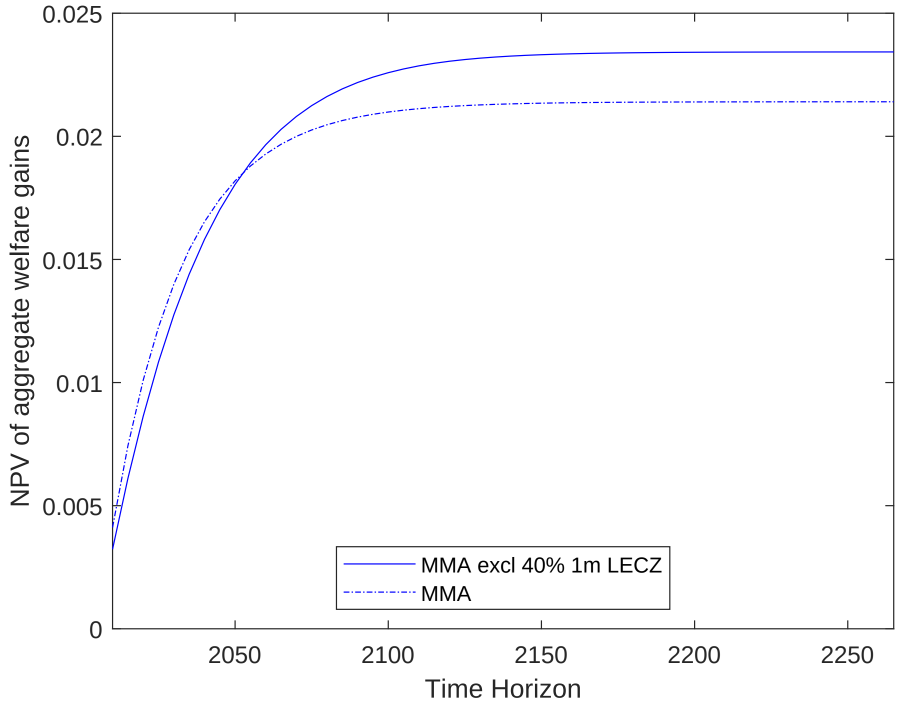
Notes: Net present value of aggregate welfare gains versus a scenario in which no roads had been upgraded, in a scenario with a 1 meter rise in the sea level realized gradually over 100 years. Counterfactual 'maximizing market access' maximizes pairwise market access between districts. Counterfactuals 'maximizing market access excluding 50%/ 40%/ 33% 1m zone' maximize pairwise market access excluding connections for districts with more than 50%/ 40%/ 33% of their land area below 1 meter.

Figure 8: Welfare gains from counterfactual road investments without sea level rise



Notes: Net present value of aggregate welfare gains versus a scenario in which no roads had been upgraded, in a scenario with no future sea level rise. Counterfactual 'maximizing market access' maximizes pairwise market access between districts. Counterfactuals 'maximizing market access excluding 50%/ 40%/ 33% 1m zone' maximize pairwise market access excluding connections for districts with more than 50%/ 40%/ 33% of their land area below 1 meter.

Figure 9: Dynamic aggregate welfare gains from counterfactual road investments with sea level rise



Notes: Compares net present value of aggregate welfare gains each period for unconstrained counterfactual 'maximizing market access' (dashed line) and counterfactual 'maximizing market access excluding 40% 1m zone' (solid line), as the time horizon over which welfare gains are aggregated increases. Welfare gains relative to a scenario in which no roads had been upgraded, incorporating a 1 meter rise in the sea level realized gradually over 100 years. Counterfactual 'maximizing market access' maximizes pairwise market access between districts. Counterfactual 'maximizing market access excluding 40% 1m zone' maximizes pairwise market access excluding connections for districts with more than 40% of their land area below 1 meter.

Table 2: Robustness tests

% welfare gains from realized and counterfactual road investments

	Realized upgrades		Maximize market access		Maximize market access excl 40% 1m LECZ		Maximize market access excl 33% 1m LECZ	
	1m SLR	No SLR	1m SLR	No SLR	1m SLR	No SLR	1m SLR	No SLR
Central simulations	1.37%	1.56%	2.14%	2.29%	2.34%	1.80%	2.30%	1.73%
$\beta = 0.986$	1.20%	1.56%	2.02%	2.29%	2.85%	1.80%	2.82%	1.74%
$\beta = 0.94$	1.42%	1.56%	2.18%	2.29%	2.19%	1.80%	2.14%	1.73%
Coastal productivities climate impacts	1.37%	1.56%	2.14%	2.29%	2.34%	1.80%	2.29%	1.73%
Coastal productivities secular trends	1.33%	1.53%	2.06%	2.21%	2.28%	1.74%	2.23%	1.68%
Coastal amenities	1.37%	1.56%	2.14%	2.29%	2.37%	1.80%	2.32%	1.74%
Real value of output in rest of world	1.40%	1.59%	2.23%	2.37%	2.41%	1.86%	2.37%	1.80%
Myopia	0.66%	1.56%	1.16%	2.29%	1.85%	1.80%	1.85%	1.73%
100 year depreciation of investments	1.35%	1.53%	2.11%	2.26%	2.29%	1.77%	2.24%	1.71%
30 year depreciation of investments	1.10%	1.18%	1.68%	1.75%	1.62%	1.37%	1.58%	1.32%
Formal sector wage data	1.14%	1.33%	1.44%	1.58%	1.76%	1.28%	1.72%	1.22%
$\frac{1}{\nu} = 2$	1.37%	1.56%	2.14%	2.29%	2.35%	1.80%	2.30%	1.73%
$\frac{1}{\nu} = 4$	1.37%	1.56%	2.14%	2.29%	2.34%	1.80%	2.29%	1.73%

Notes: Blue (orange) shading indicates the counterfactual that implies the highest welfare gains under the scenario with a gradual 1 meter sea level rise by 2110 (no sea level rise).

A Supplementary Tables and Figures

Figure A1: Natural hazard vulnerability in Vietnam

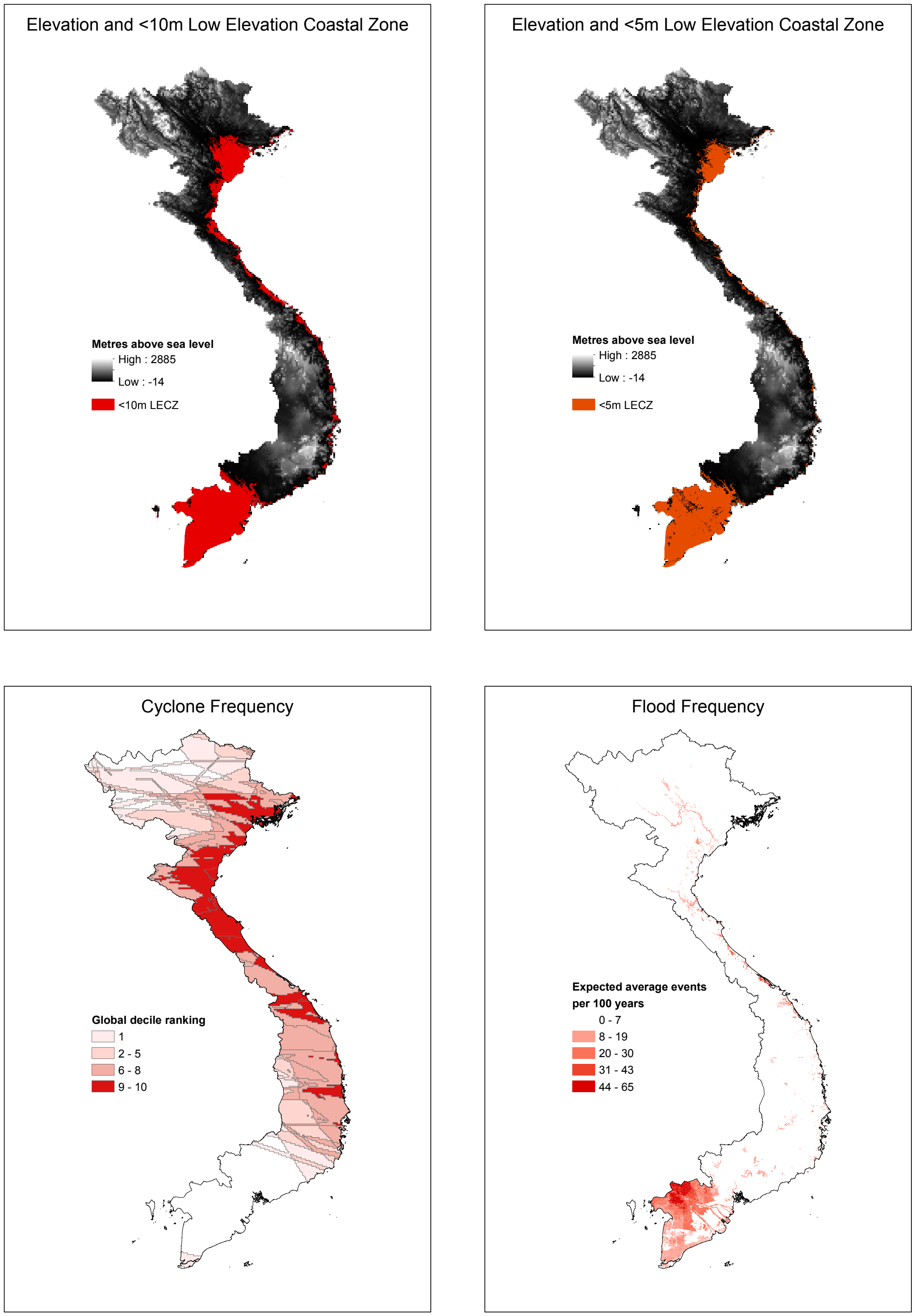
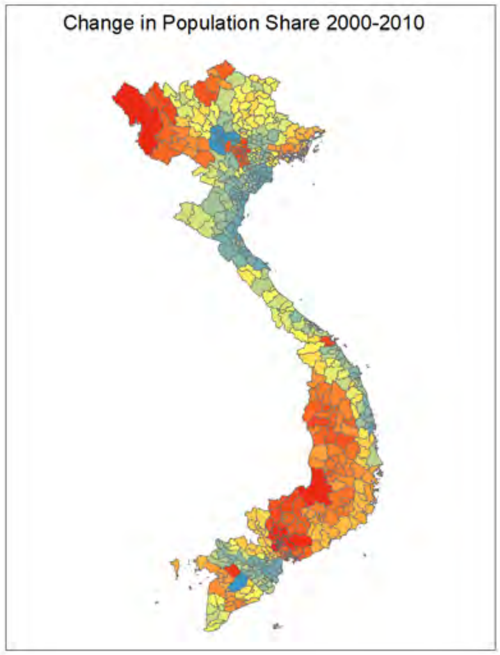
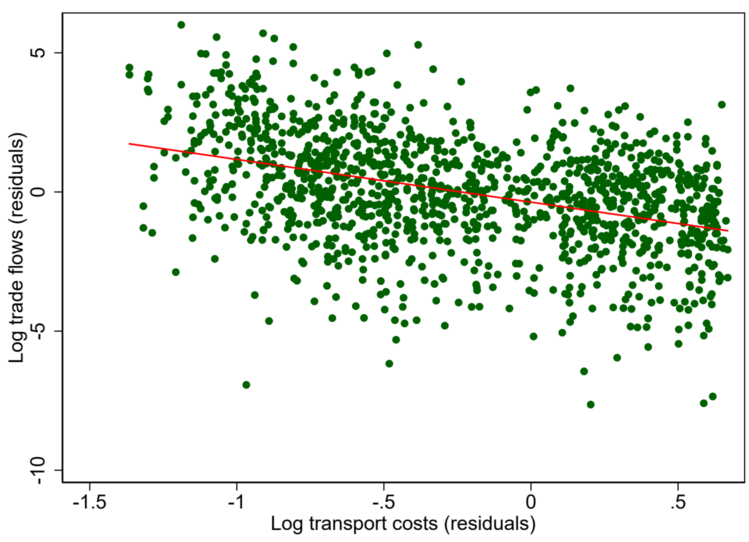


Figure A2: District-level population changes 2000-2010



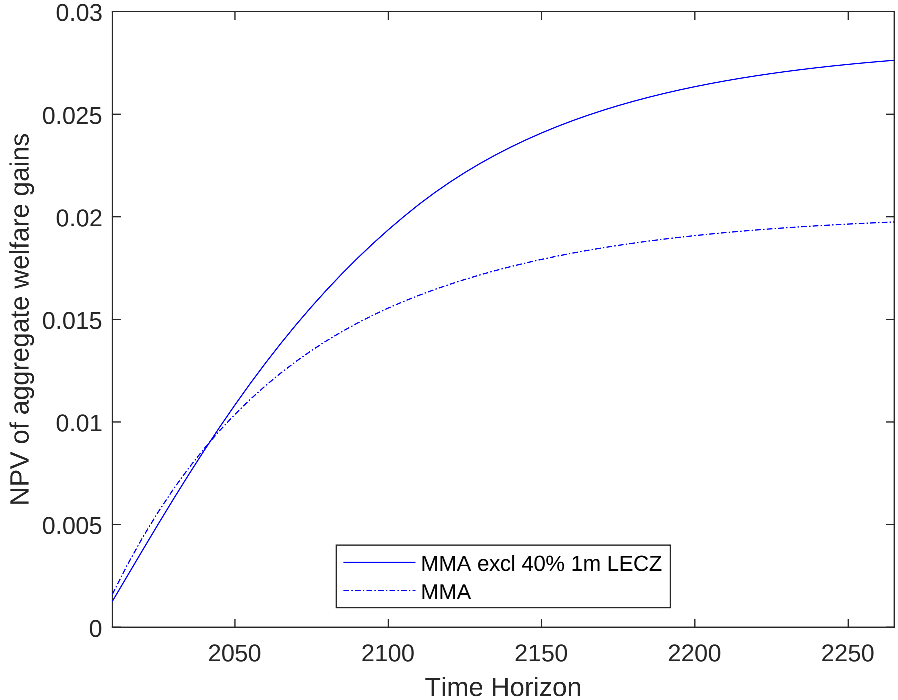
Notes: Data are reported at the level of district-based spatial units. Red (blue) units indicate higher (lower) values.

Figure A3: Inter-provincial gravity in goods trade



Notes: Red line denotes linear fit; slope -2.0.

Figure A4: Dynamic aggregate welfare gains from counterfactual road investments with sea level rise, $\beta = 0.986$



Notes: Compares net present value of aggregate welfare gains each period for unconstrained counterfactual 'maximizing market access' (dashed line) and counterfactual 'maximizing market access excluding 40% 1m zone' (solid line), as the time horizon over which welfare gains are aggregated increases. Welfare gains relative to a scenario in which no roads had been upgraded, incorporating a 1 meter rise in the sea level realized gradually over 100 years. Counterfactual 'maximizing market access' maximizes pairwise market access between districts. Counterfactual 'maximizing market access excluding 40% 1m zone' maximizes pairwise market access excluding connections for districts with more than 40% of their land area below 1 meter.

B Data Appendix

B.1 Economic Data

B.1.1 Vietnam Household Living Standards Survey (VHLSS)

The VHLSS has been conducted biennially by the General Statistics Office of Vietnam since 2002. These surveys collect information on demographics, education, health, employment, income, consumption, housing and participation in poverty alleviation programs. In each round, some respondents are administered the full survey questionnaire (29,530 households in 2002, 9,402 in 2010) and a larger number of respondents are administered a shorter version excluding the expenditure module (75,000 households in 2002, 69,360 in 2010). Responses to the former are representative at the level of Vietnam's six geographic regions and for rural/ urban areas, while those to the latter are representative at the provincial level (GSO (2010a), Lanjouw et al. (2013)).

B.1.2 Vietnam Enterprise Census (VEC)

The VEC has been conducted annually by the General Statistics Office of Vietnam since 2000. The census provides firm-level data covering all economic units with their own legal status, independent business accounts and more than 10 employees. Primary, manufacturing and services industries are included, and the data collected includes firm ownership, industry, location, age, employees, employees' compensation and fixed capital. There are a total of 42,044 firm-level observations in 2000 and 287,853 observations in 2010. The total reported labor force employed by these firms represented 4% and 11% of the total population in 2000 and 2010 respectively. Each firm for which data is reported in the VEC is assigned to a spatial unit based on its province and district identifiers. For each firm, I calculate the average annual wage per worker as the sum of salaries and salary equivalents paid to all workers divided by the number of workers. Each spatial unit average wage is then obtained as the mean value across all firms in the spatial unit, excluding 1% outliers. Similar results are obtained using the median wage across all firms in the spatial unit.

B.2 Transport Network Data

This section describes how transport network data was constructed from manually digitized maps of Vietnam's road, inland waterway and coastal shipping networks in 2000 and 2010. I then describe the data used to assign to each segment of this network a direct economic cost of transportation per ton-km, a travel time cost associated with time spent in transit and a one-off mobilization charge per ton. Together, these datasets are used to calculate bilateral trade costs between any two locations on the network or from these locations to international markets.

B.2.1 Roads

I obtain road network data from the 2000 and 2010 editions of ITMB Publishing's detailed International Travel Maps of Vietnam, which show the location of freeways, dual carriageways, major, minor and other roads. I geo-referenced each map and manually traced the location of each road category to obtain a GIS shapefile of the entire road network in each road category in 2000 and 2010, shown in Figure 3. The total length of the road network captured in this exercise is 45,741km in 2000 and 45,770km in 2010. National transport studies in 2000 and 2010 (JICA (2000), JICA (2010)) report the total lengths of roads at the national (15,250km in 2000/ 17,000km in 2010), provincial (17,449km/ 23,000km), district (36,372km/ 55,000km) and commune/village (131,455km/ 141,000km) level. As such, the road network data used in this analysis should cover the entire national and provincial road networks, and a sizable share of of the district network. Since the object of interest for my analysis is the road network that facilitates trade and migration between spatial units at a slightly more aggregated level that the district level, the coverage of my road data seems sensible.

Direct economic costs per ton-km and travel speed are allowed to vary with road type (freeway/ dual carriageway/ major road/ minor road/ other road), surface slope and surface condition.

To obtain speed data, I first assign each segment of road in 2000 and 2010 a designed speed based on its type and slope, and then adjust these downwards to obtain realized speeds based on a calibrated value for the average road surface condition across the network. I obtain road types from the mapped road networks. Surface slope is calculated using the elevation data described in Section 3.1 and the 'Slope' tool in ArcGIS Spatial Analyst, and discretized into three bins to denote flat, hilly and mountainous terrain[30]. JICA (2000) presents data on the designed speed for different road types in flat, hilly and mountainous regions. For comparability with this data, I assume that the freeways mapped in my road transport network correspond to roads with 4 x 3.75m lanes, dual carriageways to 2 x 3.75m lanes, major roads to 2 x 3m lanes, minor roads to 1 x 3.5m lanes and other roads to 1 x 3m lanes.

I assume that the average road surface condition across the network is constant and calibrate this based on the average percentage of designed speed achieved on Vietnam's roads using data from JICA (2000) and Blancas and El-Hifnawi (2013). JICA (2000) estimates that, while 100% of the designed speed can be achieved on roads with good surface condition, this falls to 80%, 50% and 30% when the road condition is fair, poor and very poor respectively. I do not have data on the surface condition of all roads in Vietnam in 2000 and 2010, so I calibrate the average road surface condition across the network based on evidence in Blancas and El-Hifnawi (2013) that in 2010 an average truck speed of 40 km/hr is 'consistently corroborated in interviews with road transport carriers'. I therefore calculate the average road surface condition across the country (measured in percentage of designed speed achieved) such that the average travel speed on the network of roads used by truckers (assumed to exclude the category 'other roads', which corresponds to sub-national level roads) in 2010 is 40 km/hr. This calculation suggests that on average 72% of the designed speed is achieved, corresponding to fair road surface conditions according to the JICA (2000) descriptions. This is

[30]The size of these bins is determined by ArcGIS's 'natural breaks' classification, which partitions data into a given number of classes based on the size of valleys in the data distribution. This gives gradient bins which correspond closely to those used to denote flat, hilly and mountainous terrain in studies of the geometric design of roads across countries (e.g. JICA (2014), Tanzania Ministry of Works (2011)).

consistent with evidence in JICA (2010) that 43% of national highways were in good condition, 37% average and 20% bad or very bad. To calculate realized travel speeds on each segment of the road network, I therefore assume that road surface conditions are such that 72% of the designed speed can be achieved in both 2000 and 2010 (note that average speeds still increase significantly due to substantial road upgrades). Based on this and the designed speed for roads of different types and slopes, I assign a travel speed to each segment of the road network in 2000 and 2010.

I use JICA (2000) data on average truck mobilization costs and cargo transportation costs per ton-km in 2000. I assume that the mobilization cost is constant across the road network but that the average cost per ton-km applies at the average travel speed on the network of roads used by truckers (32km/hr in 2000). I then apply estimated adjustment factors to allow the cost per ton-km to vary at different road speeds[31]. To obtain 2010 figures, I use evidence from Blancas and El-Hifnawi (2013) that the cost per ton of cargo transport over the 4000km round trip along the North-South axis in 2010 was $110.5. I assume that the proportion of this attributable to mobilization charges is the same in 2010 as in 2000 and that the cost per ton-km again applies at the average travel speed across the road network used by truckers (40 km/hr in 2010), scaling by the adjustment factors to obtain costs per ton-km at different road speeds.

B.2.2 Inland waterways

In contrast to the road network, the inland waterway network did not change significantly over the study period (JICA (2000), JICA (2010))[32]. I therefore map only one version of the inland waterway network, and use this for both the 2000 and 2010 analyses. The inland waterway network was traced manually in GIS from maps of the network in the JICA (2000) technical report on inland waterways, which shows the location of inland waterways in each of six classes characterized by different dimensions and therefore vessel capacities. This network was also cross-referenced with dimensions for major inland waterway routes in 2009 reported in Blancas and El-Hifnawi (2013) to verify that the network and channel classifications remained broadly unchanged. The inland waterway network is shown in Figure A5.

Blancas and El-Hifnawi (2013) estimate that the average sailing speed of self-propelled barges of all sizes on the inland waterway network is 9 km/hr, slightly lower than the typical design speed of 10 km/hr. Given minimal changes in the inland waterway network between 2000 and 2010, this value is used in both years. Blancas and El-Hifnawi (2013) provide estimates of 2010 loading and unloading costs per ton for inland waterway transportation and cargo transport costs per ton-km for ships of varying capacities[33]. For 2010 calculations, I assign the former as the mobilization cost for all inland waterway journeys, and assign variable costs per ton-km based on the vessel capacities

[31] JICA (2000) estimates adjustment factors of 1 for speeds of 60+ km/hr, 1.07 at 50 km/hr, 1.17 at 40 km/hr, 1.31 at 30 km/hr, 1.53 at 20 km/hr and 2.01 at 15 km/hr.

[32] Consistent with this, investment in the inland waterway sector over the period represented only 2% of transport sector funding between 1999 and 2007 (Blancas and El-Hifnawi (2013)).

[33] Blancas and El-Hifnawi (2013) also consider variation in cost per cargo ton-km by trip distance for each ship type. As the costs per ton-km vary much less significantly across trip distances than vessel capacities, I use the authors' baseline of costs per ton-km based on a 150 km trip for all ship types.

permissible on waterways of different classes. JICA (2000) provides average estimates in 2000 for mobilization charges per ton (again assigned to all inland waterway journeys) and transport costs per ton-km. To calculate variable costs in 2000, I assume that the midpoint of the JICA (2000) figures applies to Class 3 waterways, and obtain values for other waterway classes using the ratios of variable costs per ton-km across waterway classes from the 2010 data.

These calculations reveal that, while the slowest of the transport modes considered here, inland waterway transportation is characterized by significantly lower direct costs per ton-km of cargo than road transport and lower mobilization charges per ton than coastal shipping.

B.2.3 Coastal shipping

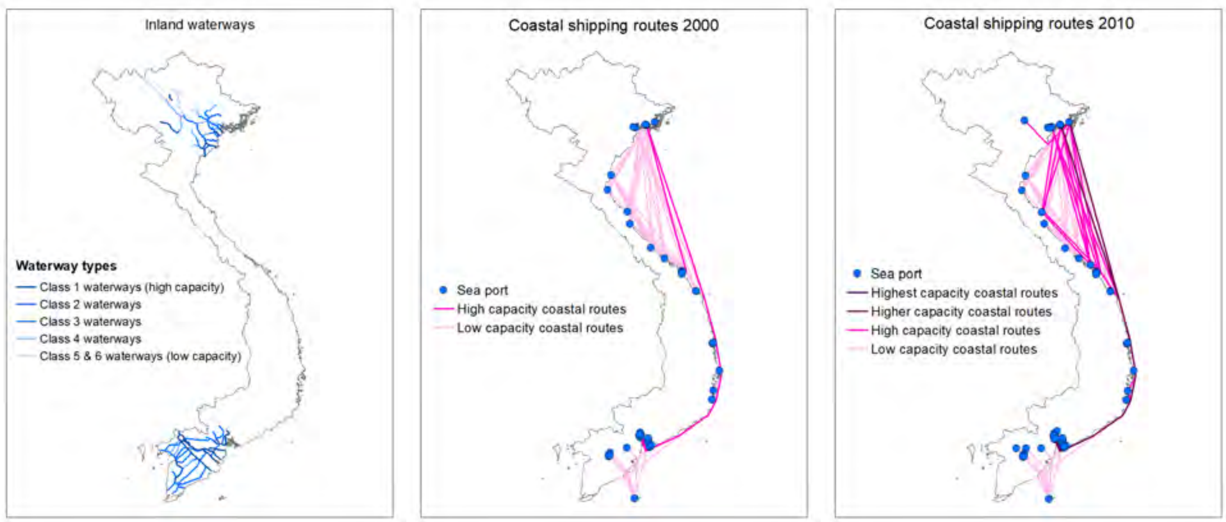
Coastal shipping routes are mapped based on the location of Vietnam's sea ports in 2000 and 2010. The locations of ports are taken from the website of the Vietnam Seaports Association. Data on which ports were operational and the maximum vessel sizes that were accepted in each port in 2000 and 2010 are based on the *'List of Seaports in the Master Plan on the Development of Vietnam's Seaport System till the Year 2010'*, *'List of Seaports in the Master Plan on Development of Vietnam's Seaport System through 2020'* and Blancas and El-Hifnawi (2013)[34]. The location of sea ports in 2000 and 2010 are shown in Figure A5, which also shows coastal shipping routes between them.

To map coastal shipping routes between these sea ports, I obtained the entire coastline of mainland Vietnam was obtained from Natural Earth and for both the 2000 and 2010 networks of seaports mapped the shortest route between neighboring ports. Estimates of coastal shipping speeds are based on data for the key shipping route between Haiphong and Ho Chi Minh City. The total time for the 3216 km round trip was estimated to be 7 days for all vessel sizes in 2010 (Blancas and El-Hifnawi (2013)), giving an average travel speed of 19km/hr. This is used as the average coastal shipping speed on all routes in both 2000 and 2010 calculations.

Direct economic costs of coastal shipping between each of Vietnam's seaports are allowed to vary with vessel size. In each year, I divide seaports into four bins based on their maximum vessel capacity and assign the average maximum vessel capacity of the ports in a bin to each port in that bin. I then choose the vessel size for journeys between each origin and destination port to be whichever is the lower of the assigned vessel capacities of the origin and destination ports in the relevant year. This allows me to subdivide the full network of coastal shipping routes in each year into four categories according to the vessel size that can be accommodated on each route; each of these categories is characterized by different economic costs of cargo transportation.

[34]For most ports, these three documents report whether the port was operational in 1999 and 2009 and their maximum vessel capacity in each of these years. For those ports where this data was not available from these documents, I used searches of other public sources to determine whether the port was operational in 2000 and 2010. For operational ports, I then estimated maximum vessel capacities in 2000 and 2010 based on current maximum vessel capacities for each port reported on the Vietnam Seaports Association website and average percentage growth rates in maximum vessel capacity across all ports with available data.

Figure A5: Inland waterway and coastal shipping networks



The key data sources for the economic cost calculations are again JICA (2000), which reports average values for coastal shipping costs per ton-km and mobilization charges in 2000, and Blancas and El-Hifnawi (2013), which provides 2010 shipping costs per ton for the Haiphong - Ho Chi Minh City route for vessels of different sizes. For 2000 calculations, I assume that the JICA (2000) figures for variable costs and mobilization charges are for a vessel of average size. I estimate these costs for vessels of other sizes by assuming that shipping costs per ton decrease with vessel size at the same rate as demonstrated in the 2010 data for the Haiphong - Ho Chi Minh City route, and that these decreases apply equally to mobilization charges and variable costs. For 2010 calculations, I use the Blancas and El-Hifnawi (2013) data on total shipping costs per ton for the Haiphong - Ho Chi Minh City route by vessel size, and the share of mobilization costs implied by the 2000 data[35]. The relevant variable transport cost per ton-km is assigned to each stretch, but the assigned mobilization cost on all routes is an average for the relevant year.

In terms of direct economic costs, coastal shipping incurs the lowest variable costs per ton-km of all modes, but the highest mobilization charges. Coastal shipping speeds are intermediate between those of road transport and inland waterways.

B.2.4 International seaports

The subset of seaports that are international seaports are obtained using data on domestic and international throughput at Vietnam's seaports in 2000 and 2010 from the Vietnam Seaports Association. In each year, I classify a seaport as an international seaport if it accounts for over 1% of the country's entire international cargo throughput and/or over 50% of the port's throughput is

[35]For vessel sizes outside the estimated range in both years, I assume the continuation of a linear trend in the relationship between vessel size and shipping cost from the nearest interval for which data is available.

international in the relevant year. By this definition, the international seaports considered account for 98% of the country's total international cargo throughput in each year.

B.2.5 Connecting roads

Because the location of each spatial unit is assigned to the longitude and latitude of its centroid, it is not always the case that the assigned location of each spatial unit lies directly on the mapped transportation network. In order to calculate bilateral transport costs between all spatial units, each spatial unit centroid is connected to the nearest point on the road network (and the inland waterway network if this is closer). Similarly, where sea ports did not coincide exactly with a spatial unit centroid or a point on the road/ inland waterway network, I connected them to the nearest point on the road network (and the inland waterway network if closer). These 'feeder' roads are assigned a travel speed and cost equivalent to the most costly type of road ('other' road on mountainous terrain). The only exceptions are the few spatial units which are islands off Vietnam's coast: these are instead assigned a travel speed and cost equivalent to a Class 1 waterway.

I allow movement between different types of road and the inland waterway network wherever they connect (albeit incurring the relevant mobilization cost), but only allow switches on to or off coastal shipping routes at sea ports.

B.2.6 Monetizing travel time costs

Travel time costs in 2000 are monetized using a weighted average of estimated cargo time costs by commodity type in 2000 from JICA (2000), where the weights are the share of each commodity in 1999 inter-provincial freight traffic demand from the same source. 2010 figures are obtained by applying the commodity-specific price indices from 2000-2010 for each commodity from GSO (2005) and GSO (2010b), and averaging using weights given by the share of each commodity in 2008 inter-provincial freight traffic demand from JICA (2010).

B.2.7 Intra spatial unit trade costs

Since the location of each spatial unit is assigned to its centroid, the Dijkstra algorithm would estimate that trade *within* each spatial unit is costless. Analyses that calibrate trade costs as a function of distance alone have addressed this problem by approximating intra-unit trade costs based on the average distance traveled to the center of a circular unit of the same area from evenly-distributed points within it, given by $\frac{2}{3}(area/\pi)^{1/2}$ (e.g. Redding and Venables (2004), Au and Henderson (2006a)). Since my analysis focuses on changes in transport infrastructure, distance-based measures will not be appropriate. However, I use the same intuition that the average distance traveled from points inside a circular unit to its center will be two thirds of the unit's radius. I assume that intra-unit trade occurs via road given the comparative advantage of road transport over shorter distances. For each spatial unit, I calculate both the travel cost along the road network and the geodesic distance from the unit's centroid to the nearest point at which the road network intersects the unit's border. I then scale the travel cost (net of the road mobilization cost) by the ratio between the measured geodesic distance and the radius of a circle with the unit's total land area. I use two thirds of this value added to the road mobilization cost as my estimate of the intra-unit bilateral trade cost.[36]

B.3 Road construction costs

This section uses data on the realized costs of individual road construction projects in Vietnam from 2000 to 2010 to validate the construction cost function in Equation (23) in this empirical setting. This construction cost function, based on the engineering literature, yields the relative road construction cost for area cells on different terrains and is used to ensure cost-neutrality of the counterfactual networks considered relative to the status quo upgrades.

Data was collected on the reported actual cost of road construction and upgrade projects in Vietnam from 2000 to 2010 from the World Bank's Road Costs Knowledge System dataset (Bosio et al. (2018)); reports of the Asian Development Bank (ADB (2001), ADB (2007), ADB (2009), ADB (2019)) and Japan International Cooperation Agency (Pham (2015), JICA (2013), Vietnam-Japan Joint Evaluation Team (2006), Vietnam-Japan Joint Evaluation Team (2007), Inazawa (2016)); and Vietnamese language sources from Logistics Vietnam (Logistics Viet Nam (2020)), Directorate for Roads Vietnam (Directorate for Roads of Vietnam (2020)) and local news reporting[37]. This yielded costs for 17 projects with sufficient geographic detail to be mapped to specific stretches of the road network. The cost per kilometer of new road lane construction projects was standardized relative to a single standard 3.7 meter lane upgrade, and the cost of lane upgrade projects to 50% of new lane construction.

The mapped road construction projects have good coverage across different regions and types of terrain across Vietnam, as shown in Figure A6. The routes corresponding to these projects were intersected with the relative road construction cost grid yielded by Equation (23). The average construction cost implied by Equation (23) along each route was then plotted against the cost per kilometer for that route in millions of US dollars from the road construction projects data. The results are shown in Figure A7 and demonstrate that the construction cost estimates based on the

[36]For the seven districts that are groups of islands, I instead obtain the minimum bounding circle enclosing each group of islands, and estimate the intra-district trade cost as the cost of traversing two thirds of the radius of this circle, assuming the same travel costs as along class 1 waterways.

[37]http://mt.gov.vn/phunu/tin-tuc/5315/quang-ninh--chuan-bi-dau-tu-du-an-xay-dung-quoc-lo-4b.asp,http://baobariavungtau.com.vn/kinh-te/200808/Quy-iV-nam-2008-Khoi-cong-nang-cap-mo-rong-quoc-lo-51-264795/,https://vnexpress.net/khoi-cong-tuyen-cao-toc-dau-tien-o-mien-trung-2756877.html,https://baodautu.vn/dau-tu-18377-ty-dong-xay-dung-cao-toc-ninh-binh--thanh-hoa-d26477.html,http://mt.gov.vn/tk/tin-tuc/16200/du-an-duong-cao-toc-cau-gie---ninh-binh-(giai-doan-i).aspx,https://gkg.com.vn/thong-tin-moi-duong-cao-toc-thanh-pho-ho-chi-minh-trung-luong/,http://www.tapchigiaothong.vn/cao-toc-phap-van--cau-re-con-duong-dep-o-cua-ngo-phia-nam-thu-do-ha-noi-d85583.html,https://daklak.gov.vn/web/english/-/buon-ma-thuot-nha-trang-highway-has-four-lanes-total-investment-of-19-500-billion-vnd,https://mt.gov.vn/vn/tin-tuc/45211/cao-toc-tp-hcm---long-thanh---dau-giay-duoc-danh-gia-la-cong-trinh-co-chat-luong-la-vuot-troi-.aspx,http://mt.gov.vn/en/news/111/hn-thai-nguyen-new-national-highway-3-opens-to-traffic.aspx,https://sapaexpress.com/vn/tuyen-duong-cao-toc-noi-bai-lao-cai-chinh-thuc-hoat-dong.html,http://baochinhphu.vn/Doi-song/Cao-toc-Phap-VanCau-Gie-Tiep-tuc-cham-vi-vuong-mat-bang/336344.vgp,https://cafeland.vn/tin-tuc/nhung-cau-duong-bo-nao-sap-duoc-hoan-thanh-o-tphcm-76250.html.

engineering cost function fit reported road construction costs from these sources well. This provides reassurance that the construction cost at Equation (23) provides a sensible basis for ensuring cost-neutrality of the counterfactual networks considered.

Figure A6: Mapped road construction projects

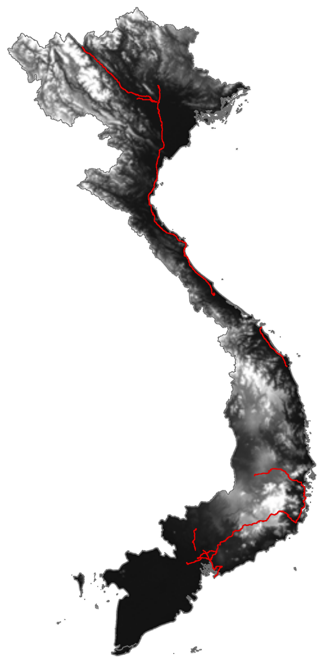
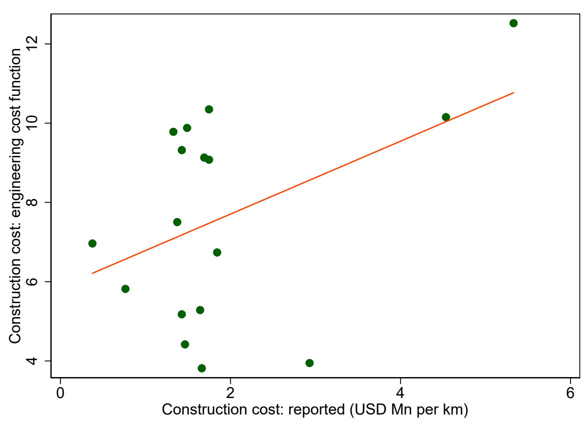


Figure A7: Road construction cost validation



C Solution algorithm with unanticipated sea level rise

The central estimates assume that agents are perfectly foresighted about the future evolution of the economy's fundamentals, including the effects of sea level rise. Under the alternative assumption of myopic agents, solving for the sequential equilibrium is more complex, since in each period the model must now be solved forward taking as given the set of initial conditions, an assumed path for the values of the model's parameters and the solution to the sequential equilibrium in the absence of any shock arriving that period. This Appendix outlines the method used to solve for the sequential equilibrium in the case where myopic agents expect that sea level rise will occur in line with climate projections 50 years into the future but that levels will stabilize thereafter.

In this case, the solution method uses agents' behavior before the arrival of the shock to construct differenced equations for $Y_{n,t+1}$, $\frac{m_{in,t+1}}{m_{in,t}}$ and $L_{n,t}$, which can be used together with equilibrium conditions (16) and (17) to solve for the sequential equilibrium. Let $X\left(\Theta^{s}\right)$ denote the variable X according to the information available in period s. Recall that at $t=0$ (2010), agents expect gradual inundation over the periods $t=1$ to $t=9$, with sea levels maintained at their $t=9$ levels thereafter. At $t=10$ (2060), agents learn that the gradual inundation will instead continue. Take as given the set of initial conditions $L_{n,0}$, $m_{in,-1}$, $w_{n,0}$ and E_{2010}; an assumed time path for land areas and transport costs based on the information available during each time period; and the solution (computed previously) to the sequential equilibrium in the absence of any shocks. In this case, the equilibrium conditions for $Y_{n,t+1}$, $\frac{m_{in,t+1}}{m_{in,t}}$ and $L_{n,t}$ are derived at Appendix D and summarized here.

The equilibrium conditions for expected lifetime utility and migration shares expressed in relative time differences in the absence of any shocks are as derived previously (equations A14 and A15), repeated here with the available information set made explicit:

$$Y\left(\Theta^{0}\right)_{n,t+1} = \left[\frac{\left(\frac{w\left(\Theta^{0}\right)_{n,t+1}}{w\left(\Theta^{0}\right)_{n,t}}\right)^{\alpha}}{\left(\frac{P\left(\Theta^{0}\right)_{n,t+1}}{P\left(\Theta^{0}\right)_{n,t}}\right)^{\alpha}\left(\frac{L\left(\Theta^{0}\right)_{n,t+1}/L\left(\Theta^{0}\right)_{n,t}}{H\left(\Theta^{0}\right)_{n,t+1}/H\left(\Theta^{0}\right)_{n,t}}\right)^{1-\alpha}}\right]^{\frac{1}{\nu}} \times \sum_{k\in N} m\left(\Theta^{0}\right)_{kn,t}\left(Y\left(\Theta^{0}\right)_{k,t+2}\right)^{\beta} exp\left[\frac{1}{\nu}\left(B\left(\Theta^{0}\right)_{k,t+1}-B\left(\Theta^{0}\right)_{k,t}\right)\right] \tag{A1}$$

$$\frac{m\left(\Theta^{0}\right)_{in,t+1}}{m\left(\Theta^{0}\right)_{in,t}} = \frac{\left(Y\left(\Theta^{0}\right)_{i,t+2}\right)^{\beta}\left(exp\left[B\left(\Theta^{0}\right)_{i,t+1}-B\left(\Theta^{0}\right)_{i,t}\right]\right)^{\frac{1}{\nu}}}{\sum_{k\in N} m\left(\Theta^{0}\right)_{kn,t}\left(Y\left(\Theta^{0}\right)_{k,t+2}\right)^{\beta}\left(exp\left[B\left(\Theta^{0}\right)_{k,t+1}-B\left(\Theta^{0}\right)_{k,t}\right]\right)^{\frac{1}{\nu}}} \tag{A2}$$

In all periods after $t=10$, the period in which the unanticipated shock arrives and updated information on the path of the economy's fundamentals becomes available, define $Y\left(\Theta^{10}\right)_{n,10} = \left[exp\left(V\left(\Theta^{10}\right)_{n,10}-V\left(\Theta^{0}\right)_{n,9}\right)\right]^{\frac{1}{\nu}}$ and $Y\left(\Theta^{10}\right)_{n,t+1} = \left[exp\left(V\left(\Theta^{10}\right)_{n,t+1}-V\left(\Theta^{10}\right)_{n,t}\right)\right]^{\frac{1}{\nu}}$ for $t\geq 10$. It is shown in Appendix D that this gives rise to the following system of equations:

$$Y\left(\Theta^{10}\right)_{n,10} = \left[\frac{\left(\frac{w\left(\Theta^{10}\right)_{n,10}}{w\left(\Theta^{0}\right)_{n,9}}\right)^{\alpha}}{\left(\frac{P\left(\Theta^{10}\right)_{n,10}}{P\left(\Theta^{0}\right)_{n,9}}\right)^{\alpha}\left(\frac{L\left(\Theta^{10}\right)_{n,10}/L\left(\Theta^{0}\right)_{n,9}}{H\left(\Theta^{10}\right)_{n,10}/H\left(\Theta^{0}\right)_{n,9}}\right)^{1-\alpha}}\right]^{\frac{1}{\nu}}$$
$$\times \textstyle\sum_{i\in N}\left(\frac{Y\left(\Theta^{10}\right)_{i,10}}{Y\left(\Theta^{0}\right)_{i,10}}\right)^{\beta} m\left(\Theta^{0}\right)_{in,9}\left(Y\left(\Theta^{10}\right)_{i,11}\right)^{\beta}\left(exp\left[B\left(\Theta^{10}\right)_{i,10} - B\left(\Theta^{0}\right)_{i,9}\right]\right)^{\frac{1}{\nu}} \quad \text{(A3)}$$

$$Y\left(\Theta^{10}\right)_{n,t+1} = \left[\frac{\left(\frac{w\left(\Theta^{10}\right)_{n,t+1}}{w\left(\Theta^{10}\right)_{n,t}}\right)^{\alpha}}{\left(\frac{P\left(\Theta^{10}\right)_{n,t+1}}{P\left(\Theta^{10}\right)_{n,t}}\right)^{\alpha}\left(\frac{L\left(\Theta^{10}\right)_{n,t+1}/L\left(\Theta^{10}\right)_{n,t}}{H\left(\Theta^{10}\right)_{n,t+1}/H\left(\Theta^{10}\right)_{n,t}}\right)^{1-\alpha}}\right]^{\frac{1}{\nu}}$$
$$\times \textstyle\sum_{k\in N} m\left(\Theta^{10}\right)_{kn,t}\left(Y\left(\Theta^{10}\right)_{k,t+2}\right)^{\beta}\left(exp\left[B\left(\Theta^{10}\right)_{i,t+1} - B\left(\Theta^{10}\right)_{i,t}\right]\right)^{\frac{1}{\nu}}, \quad t \geq 10 \quad \text{(A4)}$$

$$\frac{m\left(\Theta^{10}\right)_{in,10}}{m\left(\Theta^{0}\right)_{in,9}} = \frac{\left(Y\left(\Theta^{10}\right)_{i,11}\right)^{\beta}\left(\frac{Y\left(\Theta^{10}\right)_{i,10}}{Y\left(\Theta^{0}\right)_{i,10}}\right)^{\beta}\left(exp\left[B\left(\Theta^{10}\right)_{i,10} - B\left(\Theta^{0}\right)_{i,9}\right]\right)^{\frac{1}{\nu}}}{\sum_{k\in N} m\left(\Theta^{0}\right)_{kn,9}\left(Y\left(\Theta^{10}\right)_{k,11}\right)^{\beta}\left(\frac{Y\left(\Theta^{10}\right)_{k,10}}{Y\left(\Theta^{0}\right)_{k,10}}\right)^{\beta}\left(exp\left[B\left(\Theta^{10}\right)_{k,10} - B\left(\Theta^{0}\right)_{k,9}\right]\right)^{\frac{1}{\nu}}} \quad \text{(A5)}$$

$$\frac{m\left(\Theta^{10}\right)_{in,t+1}}{m\left(\Theta^{10}\right)_{in,t}} = \frac{\left(Y\left(\Theta^{10}\right)_{i,t+2}\right)^{\beta}\left(exp\left[B\left(\Theta^{10}\right)_{i,t+1} - B\left(\Theta^{10}\right)_{i,t}\right]\right)^{\frac{1}{\nu}}}{\sum_{k\in N} m\left(\Theta^{10}\right)_{kn,t}\left(Y\left(\Theta^{10}\right)_{k,t+2}\right)^{\beta}\left(exp\left[B\left(\Theta^{10}\right)_{k,t+1} - B\left(\Theta^{10}\right)_{k,t}\right]\right)^{\frac{1}{\nu}}} \quad t > 10 \quad \text{(A6)}$$

$$L\left(\Theta^{10}\right)_{n,10} = \sum_{i\in N} m\left(\Theta^{0}\right)_{ni,9} L\left(\Theta^{0}\right)_{i,9} \quad \text{(A7)}$$

$$L\left(\Theta^{10}\right)_{n,t+1} = \textstyle\sum_{i\in N} m\left(\Theta^{10}\right)_{ni,t} L\left(\Theta^{10}\right)_{i,t}, \quad t > 10 \quad \text{(A8)}$$

This is the set of equilibrium conditions that are solved together with equilibrium conditions (16), (17) and (20) for the sequential equilibrium in the case where sea level rise arrives as an unanticipated shock.

D Theory Appendix

D.1 Derivation of expected lifetime utility (Equation (1))

1. Agents choose to remain in or move to the location j that offers the largest expected benefits, net of moving costs. Let $v_{i,t}$ denote the lifetime utility of a worker in location i at time t and $V = \mathbb{E}(v)$ denote the expected lifetime utility of a representative agent with respect to the vector of idiosyncratic shocks b.

$$\begin{aligned} V_{n,t} &= \alpha ln\left(\tfrac{C_{n,t}}{\alpha}\right) + (1-\alpha) ln\left(\tfrac{H_{n,t}}{1-\alpha}\right) + \mathbb{E}\left\{max_{i\in N}\left[\beta\mathbb{E}\left(v_{i,t+1}\right) - \mu_{in} + B_{i,t} + b_{i,t}\right]\right\} \\ &= \alpha ln\left(\tfrac{C_{n,t}}{\alpha}\right) + (1-\alpha) ln\left(\tfrac{H_{n,t}}{1-\alpha}\right) + \mathbb{E}\left\{\textstyle\sum_{i\in N}\left(\beta V_{i,t+1} - \mu_{in} + B_{i,t} + b_{i,t}\right)\right\} \\ &\quad \times Pr\left[\left(\beta V_{i,t+1} - \mu_{in} + B_{i,t} + b_{i,t}\right) \geq \left(\beta V_{m,t+1} - \mu_{mn} + B_{m,t} + b_{m,t}\right), m = 1, ..., N\right] \\ &= \alpha ln\left(\tfrac{C_{n,t}}{\alpha}\right) + (1-\alpha) ln\left(\tfrac{H_{n,t}}{1-\alpha}\right) + \textstyle\sum_{i\in N}\int\left(\beta V_{i,t+1} - \mu_{in} + B_{i,t} + b_{i,t}\right) f\left(b_{i,t}\right) \\ &\quad \times \textstyle\prod_{m\neq i} F\left(\beta\left(V_{i,t+1} - V_{m,t+1}\right) - \left(\mu_{in} - \mu_{mn}\right) + \left(B_{i,t} - B_{m,t}\right) + b_{i,t}\right) db_{i,t} \\ &= \alpha ln\left(\tfrac{C_{n,t}}{\alpha}\right) + (1-\alpha) ln\left(\tfrac{H_{n,t}}{1-\alpha}\right) \\ &\quad + \textstyle\sum_{i\in N}\int\left(\beta V_{i,t+1} - \mu_{in} + B_{i,t} + b_{i,t}\right) f\left(b_{i,t}\right) \prod_{m\neq i} F\left(\bar{b}_{im,t} + b_{i,t}\right) db_{i,t} \end{aligned} \tag{A9}$$

where $\bar{b}_{im,t} = \beta\left(V_{i,t+1} - V_{m,t+1}\right) - \left(\mu_{in} - \mu_{mn}\right) + \left(B_{i,t} - B_{m,t}\right)$.

2. The Gumbel distribution with parameters $(-\gamma\nu, \nu)$ (where γ is Euler's constant) has cumulative distribution function:

$$F(b) = exp\left(-exp\left(-\frac{b}{\nu} - \gamma\right)\right)$$

and density function:

$$f(b) = \left(\frac{1}{\nu}\right) exp\left(-\frac{b}{\nu} - \gamma - exp\left(-\frac{b}{\nu} - \gamma\right)\right)$$

3. Substituting the cumulative distribution function and density function into equation (A9) yields the following::

$$\begin{aligned} V_{n,t} &= \alpha ln\left(\tfrac{C_{n,t}}{\alpha}\right) + (1-\alpha) ln\left(\tfrac{H_{n,t}}{1-\alpha}\right) + \textstyle\sum_{i\in N}\int\left(\beta V_{i,t+1} - \mu_{in} + B_{i,t} + b_{i,t}\right) \\ &\quad \times \left(\tfrac{1}{\nu}\right) exp\left(-\tfrac{b_{i,t}}{\nu} - \gamma - exp\left(-\tfrac{b_{i,t}}{\nu} - \gamma\right)\right) \textstyle\prod_{m\neq i} exp\left(-exp\left(-\tfrac{\bar{b}_{im,t} + b_{i,t}}{\nu} - \gamma\right)\right) db_{i,t} \\ &= \alpha ln\left(\tfrac{C_{n,t}}{\alpha}\right) + (1-\alpha) ln\left(\tfrac{H_{n,t}}{1-\alpha}\right) + \textstyle\sum_{i\in N}\int\left(\beta V_{i,t+1} - \mu_{in} + B_{i,t} + b_{i,t}\right) \\ &\quad \times \left(\tfrac{1}{\nu}\right) exp\left(-\tfrac{b_{i,t}}{\nu} - \gamma - exp\left(-\tfrac{b_{i,t}}{\nu} - \gamma\right)\right) exp\left(-\textstyle\sum_{m\neq i} exp\left(-\tfrac{\bar{b}_{im,t} + b_{i,t}}{\nu} - \gamma\right)\right) db_{i,t} \\ &= \alpha ln\left(\tfrac{C_{n,t}}{\alpha}\right) + (1-\alpha) ln\left(\tfrac{H_{n,t}}{1-\alpha}\right) + \textstyle\sum_{i\in N}\int\left(\beta V_{i,t+1} - \mu_{in} + B_{i,t} + b_{i,t}\right) \\ &\quad \times \left(\tfrac{1}{\nu}\right) exp\left(-\tfrac{b_{i,t}}{\nu} - \gamma\right) exp\left(-exp\left(-\tfrac{b_{i,t}}{\nu} - \gamma\right) - \textstyle\sum_{m\neq i} exp\left(-\tfrac{\bar{b}_{im,t} + b_{i,t}}{\nu} - \gamma\right)\right) db_{i,t} \\ &= \alpha ln\left(\tfrac{C_{n,t}}{\alpha}\right) + (1-\alpha) ln\left(\tfrac{H_{n,t}}{1-\alpha}\right) + \textstyle\sum_{i\in N}\int\left(\beta V_{i,t+1} - \mu_{in} + B_{i,t} + b_{i,t}\right) \\ &\quad \times \left(\tfrac{1}{\nu}\right) exp\left(-\tfrac{b_{i,t}}{\nu} - \gamma\right) exp\left(-\textstyle\sum_{m\in N} exp\left(-\tfrac{\bar{b}_{im,t} + b_{i,t}}{\nu} - \gamma\right)\right) db_{i,t} \end{aligned}$$

4. Define $\lambda_t = ln \sum_{m \in N} exp\left(-\frac{\bar{b_{im,t}}}{\nu}\right)$ and $x_t = \frac{b_{i,t}}{\nu} + \gamma$ and $y_t = x_t - \lambda_t$:

$$\begin{aligned}
V_{n,t} &= \alpha ln\left(\frac{C_{n,t}}{\alpha}\right) + (1-\alpha)ln\left(\frac{H_{n,t}}{1-\alpha}\right) + \sum_{i \in N} \int \left(\beta V_{i,t+1} - \mu_{in} + B_{i,t} + x_t\nu - \gamma\nu\right) \\
&\quad \times \left(\frac{1}{\nu}\right) exp\left(-x_t\right) exp\left(-\sum_{m \in N} exp\left(-x_t\right) exp\left(-\frac{\bar{b_{im,t}}}{\nu}\right)\right) \nu dx_t \\
&= \alpha ln\left(\frac{C_{n,t}}{\alpha}\right) + (1-\alpha)ln\left(\frac{H_{n,t}}{1-\alpha}\right) + \sum_{i \in N} \int \left(\beta V_{i,t+1} - \mu_{in} + B_{i,t} + \nu\left(x_t - \gamma\right)\right) \\
&\quad \times exp\left(-x_t - exp\left(-\left(x_t - \lambda_t\right)\right)\right) dx_t \\
&= \alpha ln\left(\frac{C_{n,t}}{\alpha}\right) + (1-\alpha)ln\left(\frac{H_{n,t}}{1-\alpha}\right) + \sum_{i \in N} \int \left(\beta V_{i,t+1} - \mu_{in} + B_{i,t} + \nu\left(y_t + \lambda_t - \gamma\right)\right) \\
&\quad \times exp\left(-y_t - \lambda_t - exp\left(-y_t\right)\right) dy_t \\
&= \alpha ln\left(\frac{C_{n,t}}{\alpha}\right) + (1-\alpha)ln\left(\frac{H_{n,t}}{1-\alpha}\right) + \sum_{i \in N} exp\left(-\lambda_t\right) \\
&\quad \times \int \left(\beta V_{i,t+1} - \mu_{in} + B_{i,t} + \nu\left(y_t + \lambda_t - \gamma\right)\right) exp\left(-y_t - exp\left(-y_t\right)\right) dy_t \\
&= \alpha ln\left(\frac{C_{n,t}}{\alpha}\right) + (1-\alpha)ln\left(\frac{H_{n,t}}{1-\alpha}\right) + \sum_{i \in N} exp\left(-\lambda_t\right) \left[\left(\beta V_{i,t+1} - \mu_{in} + B_{i,t} + \nu\left(\lambda_t - \gamma\right)\right)\right. \\
&\quad \left. \times \int exp\left(-y_t - exp\left(-y_t\right)\right) dy_t + \nu \int y_t exp\left(-y_t - exp\left(-y_t\right)\right) dy_t\right]
\end{aligned}$$

5. The anti-derivative of $exp\left(-y - exp(-y)\right)$ is $exp\left(-exp(-y)\right)$, and $\int y \cdot exp\left(-y - exp(-y)\right) dy = \gamma$ (Patel et al. (1976)). Therefore:

$$\begin{aligned}
V_{n,t} &= \alpha ln\left(\frac{C_{n,t}}{\alpha}\right) + (1-\alpha)ln\left(\frac{H_{n,t}}{1-\alpha}\right) + \sum_{i \in N} exp\left(-\lambda_t\right) \{\left(\beta V_{i,t+1} - \mu_{in} + B_{i,t} + \nu\left(\lambda_t - \gamma\right)\right) \\
&\quad \times \left[exp\left(-exp\left(-y_t\right)\right)\right]_{-\infty}^{+\infty} + \nu\gamma\} \\
&= \alpha ln\left(\frac{C_{n,t}}{\alpha}\right) + (1-\alpha)ln\left(\frac{H_{n,t}}{1-\alpha}\right) + \sum_{i \in N} exp\left(-\lambda_t\right) \left[\beta V_{i,t+1} - \mu_{in} + B_{i,t} + \nu\left(\lambda_t - \gamma\right) + \nu\gamma\right] \\
&= \alpha ln\left(\frac{C_{n,t}}{\alpha}\right) + (1-\alpha)ln\left(\frac{H_{n,t}}{1-\alpha}\right) + \sum_{i \in N} exp\left(-\lambda_t\right) \left[\beta V_{i,t+1} - \mu_{in} + B_{i,t} + \nu\lambda_t\right] \\
&= \alpha ln\left(\frac{C_{n,t}}{\alpha}\right) + (1-\alpha)ln\left(\frac{H_{n,t}}{1-\alpha}\right) + \sum_{i \in N} exp\left(-ln \sum_{m \in N} exp\left(-\frac{\bar{b_{im,t}}}{\nu}\right)\right) \\
&\quad \times \left[\beta V_{i,t+1} - \mu_{in} + B_{i,t} + \nu ln \sum_{m \in N} exp\left(-\frac{\bar{b_{im,t}}}{\nu}\right)\right] \\
&= \alpha ln\left(\frac{C_{n,t}}{\alpha}\right) + (1-\alpha)ln\left(\frac{H_{n,t}}{1-\alpha}\right) + \sum_{i \in N} exp[-ln \sum_{m \in N} exp(-\frac{1}{\nu}(\beta\left(V_{i,t+1} - V_{m,t+1}\right) \\
&\quad - \left(\mu_{in} - \mu_{mn}\right) + \left(B_{i,t} - B_{m,t}\right)))][\beta V_{i,t+1} - \mu_{in} + B_{i,t} + \\
&\quad \nu ln \sum_{m \in N} exp\left(-\frac{1}{\nu}\left(\beta\left(V_{i,t+1} - V_{m,t+1}\right) - \left(\mu_{in} - \mu_{mn}\right) + \left(B_{i,t} - B_{m,t}\right)\right)\right)] \\
&= \alpha ln\left(\frac{C_{n,t}}{\alpha}\right) + (1-\alpha)ln\left(\frac{H_{n,t}}{1-\alpha}\right) + \sum_{i \in N} exp(-ln[exp\left(-\frac{1}{\nu}\left(\beta V_{i,t+1} - \mu_{in} + B_{i,t}\right)\right) \\
&\quad \sum_{m \in N} exp\left(-\frac{1}{\nu}\left(-\beta V_{m,t+1} + \mu_{mn} - B_{m,t}\right)\right)])[\beta V_{i,t+1} - \mu_{in} + B_{i,t} + \\
&\quad \nu ln\left[exp\left(-\frac{1}{\nu}\left(\beta V_{i,t+1} - \mu_{in} + B_{i,t}\right)\right) \sum_{m \in N} exp\left(-\frac{1}{\nu}\left(-\beta V_{m,t+1} + \mu_{mn} - B_{m,t}\right)\right)\right]]
\end{aligned}$$

$$
\begin{aligned}
= & \quad \alpha ln\left(\frac{C_{n,t}}{\alpha}\right)+(1-\alpha)ln\left(\frac{H_{n,t}}{1-\alpha}\right)+\textstyle\sum_{i\in N}\{exp[(\frac{1}{\nu}\left(\beta V_{i,t+1}-\mu_{in}+B_{i,t}\right)- \\
& \quad ln\textstyle\sum_{m\in N}exp\left(-\frac{1}{\nu}\left(-\beta V_{m,t+1}+\mu_{mn}-B_{m,t}\right)\right))][\beta V_{i,t+1}-\mu_{in}+B_{i,t}+ \\
& \quad \nu\left[-\frac{1}{\nu}\left(\beta V_{i,t+1}-\mu_{in}+B_{i,t}\right)+ln\textstyle\sum_{m\in N}exp\left(-\frac{1}{\nu}\left(-\beta V_{m,t+1}+\mu_{mn}-B_{m,t}\right)\right)\right]]\} \\
= & \quad \alpha ln\left(\frac{C_{n,t}}{\alpha}\right)+(1-\alpha)ln\left(\frac{H_{n,t}}{1-\alpha}\right)+\textstyle\sum_{i\in N}\{\frac{exp\left[\frac{1}{\nu}\left(\beta V_{i,t+1}-\mu_{in}+B_{i,t}\right)\right]}{\sum_{m\in N}exp\left(-\frac{1}{\nu}\left(-\beta V_{m,t+1}+\mu_{mn}-B_{m,t}\right)\right)} \\
& \quad \times\left[\nu ln\textstyle\sum_{m\in N}exp\left(-\frac{1}{\nu}\left(-\beta V_{m,t+1}+\mu_{mn}-B_{m,t}\right)\right)\right]\} \\
= & \quad \alpha ln\left(\frac{C_{n,t}}{\alpha}\right)+(1-\alpha)ln\left(\frac{H_{n,t}}{1-\alpha}\right)+\nu ln\textstyle\sum_{m\in N}\left(exp\left(\beta V_{m,t+1}-\mu_{mn}+B_{m,t}\right)\right)^{\frac{1}{\nu}} \\
& \quad \times\left\{\frac{\sum_{i\in N}\left(exp(\beta V_{i,t+1}-\mu_{in}+B_{i,t})\right)^{\frac{1}{\nu}}}{\sum_{m\in N}\left(exp(\beta V_{m,t+1}-\mu_{mn}+B_{m,t})\right)^{\frac{1}{\nu}}}\right\} \\
= & \quad \alpha ln\left(\frac{C_{n,t}}{\alpha}\right)+(1-\alpha)ln\left(\frac{H_{n,t}}{1-\alpha}\right)+\nu ln\textstyle\sum_{m\in N}\left(exp\left(\beta V_{m,t+1}-\mu_{mn}+B_{m,t}\right)\right)^{\frac{1}{\nu}}
\end{aligned}
$$

D.2 Derivation of migration shares (Equation (2))

1. Of agents that start period t in location n, the fraction that migrate to region i is given by the probability that location i offers the highest expected utility for agents from region n of all possible destination regions (including the region of origin):

$$
\begin{aligned}
m_{in,t} &= Pr\left[\left(\beta V_{i,t+1}-\mu_{in}+B_{i,t}+b_{i,t}\right)\geq\left(\beta V_{m,t+1}-\mu_{mn}+B_{m,t}+b_{m,t}\right),m=1,...,N\right] \\
&= \int f\left(b_{i,t}\right)\textstyle\prod_{m\neq i}F\left(\beta\left(V_{i,t+1}-V_{m,t+1}\right)-\left(\mu_{in}-\mu_{mn}\right)+\left(B_{i,t}-B_{m,t}\right)+b_{i,t}\right)db_{i,t}
\end{aligned}
$$

2. Again substituting $\bar{b_{im,t}}=\beta\left(V_{i,t+1}-V_{m,t+1}\right)-\left(\mu_{in}-\mu_{mn}\right)+\left(B_{i,t}-B_{m,t}\right)$ and the cumulative distribution function and density function of the distribution of the idiosyncratic preference draws:

$$
\begin{aligned}
m_{in,t} &= \int\left(\frac{1}{\nu}\right)exp\left(-\frac{b_{i,t}}{\nu}-\gamma-exp\left(-\frac{b_{i,t}}{\nu}-\gamma\right)\right)\textstyle\prod_{m\neq i}exp\left(-exp\left(-\frac{\bar{b_{im,t}}}{\nu}-\frac{b_{i,t}}{\nu}-\gamma\right)\right)db_{i,t} \\
&= \int\left(\frac{1}{\nu}\right)exp\left(-\frac{b_{i,t}}{\nu}-\gamma\right)exp\left(-\textstyle\sum_{m\in N}exp\left(-\frac{\bar{b_{im,t}}}{\nu}-\frac{b_{i,t}}{\nu}-\gamma\right)\right)db_{i,t}
\end{aligned}
$$

3. As in the previous derivation, define $\lambda_t=ln\sum_{m\in N}exp\left(-\frac{\bar{b_{im,t}}}{\nu}\right)$ and $x_t=\frac{b_{i,t}}{\nu}+\gamma$ and $y_t=x_t-\lambda_t$ and use the fact that the anti-derivative of $exp\left(-y-exp(-y)\right)$ is $exp\left(-exp(-y)\right)$:

$$
\begin{aligned}
m_{in,t} &= \int\left(\frac{1}{\nu}\right)exp\left(-x_t\right)exp\left(-exp\left(\lambda_t\right)exp\left(-x_t\right)\right)\nu dx_t \\
&= \int exp\left(-y_t-\lambda_t\right)exp\left(-exp\left(\lambda_t\right)exp\left(-y_t-\lambda_t\right)\right)dy_t \\
&= exp\left(-\lambda_t\right)\int exp\left(-y_t-exp\left(-y_t\right)\right)dy_t \\
&= exp\left(-\lambda_t\right) \\
&= \frac{1}{\sum_{m\in N}exp\left(\frac{1}{\nu}\left[-\beta(V_{i,t+1}-V_{m,t+1})+(\mu_{in}-\mu_{mn})-(B_{i,t}-B_{m,t})\right]\right)} \\
&= \frac{\left(exp[\beta V_{i,t+1}-\mu_{in}+B_{i,t}]\right)^{\frac{1}{\nu}}}{\sum_{m\in N}\left(exp[\beta V_{m,t+1}-\mu_{mn}+B_{m,t}]\right)^{\frac{1}{\nu}}}
\end{aligned}
$$

D.3 Derivation of consumption goods price index and the share of location n's expenditure on goods produced in location i at time t (Equations 4 and 5)

Firms set the price of their variety to maximize profits, which yields the result that the equilibrium price at n of a good produced at i at time t is a constant mark-up over marginal cost:

$$p_{ni,t}(j) = \left(\frac{\sigma}{\sigma-1}\right)\frac{d_{ni,t}w_{i,t}}{A_{i,t}} \tag{A10}$$

where $w_{i,t}$ is the wage at i at time t.

Combining equation (A10) with the zero profit condition, equilibrium employment of effective labor units for each variety is equal to a constant, $l_{i,t}(j) = \bar{l} = \sigma F$. Combining this in turn with the labor market clearing condition in each location, $\int_0^{M_{i,t}} l_{i,t}(j)dj = L_{i,t}$, the measure of varieties supplied in each location at time t is proportional to the endogenous supply of labor units in that location: $M_{i,t} = \frac{L_{i,t}}{\sigma F}$.

The consumption goods price index can then be expressed as:

$$P_{n,t}^{1-\eta} = \sum_{i\in N} P_{ni,t}^{1-\eta} = \sum_{i\in N}\left(\frac{L_{i,t}}{\sigma F}\right)^{\frac{1-\eta}{1-\sigma}}\left(\left(\frac{\sigma}{\sigma-1}\right)\frac{d_{ni,t}w_{i,t}}{A_{i,t}}\right)^{1-\eta} \tag{A11}$$

This yields an expression for trade shares:

$$\begin{aligned}
\pi_{ni} &= \left(\frac{P_{ni}}{P_n}\right)^{1-\eta} = \frac{\left(\frac{L_{i,t}}{\sigma F}\right)^{\frac{1-\eta}{1-\sigma}}\left[\left(\frac{\sigma}{\sigma-1}\right)\frac{d_{ni,t}w_{i,t}}{A_{i,t}}\right]^{1-\eta}}{\sum_{l\in N}\left(\frac{L_{l,t}}{\sigma F}\right)^{\frac{1-\eta}{1-\sigma}}\left[\left(\frac{\sigma}{\sigma-1}\right)\frac{d_{nl,t}w_{l,t}}{A_{l,t}}\right]^{1-\eta}} \\
&= \frac{A_{i,t}^{\eta-1}L_{i,t}^{\frac{1-\eta}{1-\sigma}}\left[d_{ni,t}w_{i,t}\right]^{1-\eta}}{\sum_{l\in N}A_{l,t}^{\eta-1}L_{l,t}^{\frac{1-\eta}{1-\sigma}}\left[d_{nl,t}w_{l,t}\right]^{1-\eta}} \\
&= \frac{A_{i,t}^{\eta-1}L_{i,t}^{\frac{\eta-1}{\sigma-1}}\left[d_{ni,t}w_{i,t}\right]^{1-\eta}}{\sum_{l\in N}A_{l,t}^{\eta-1}L_{l,t}^{\frac{\eta-1}{\sigma-1}}\left[d_{nl,t}w_{l,t}\right]^{1-\eta}}
\end{aligned} \tag{A12}$$

D.4 Derivation of welfare at location n at time t (Equation (21))

1. From equation (2), the share of the population who start period t in location n that choose to stay in the same location next period is given by:

$$m_{nn,t} = \frac{\left(exp\left[\beta V_{n,t+1} + B_{n,t}\right]\right)^{\frac{1}{\nu}}}{\sum_{m\in N}\left(exp\left[\beta V_{m,t+1} - \mu_{mn} + B_{m,t}\right]\right)^{\frac{1}{\nu}}}$$

which implies that:

$$ln\left(m_{nn,t}\right) = \frac{1}{\nu}\left(\beta V_{n,t+1} + B_{n,t}\right) - ln\sum_{m\in N}\left(exp\left[\beta V_{m,t+1} - \mu_{mn} + B_{m,t}\right]\right)^{\frac{1}{\nu}}$$

2. Substituting this into equation (9) gives:

$$\begin{aligned} V_{n,t} &= \alpha ln w_{n,t} - \alpha ln P_{n,t} - (1-\alpha) ln\left(\frac{(1-\alpha)L_{n,t}}{H_{n,t}}\right) + \nu ln \textstyle\sum_{i\in N}\left(exp\left[\beta V_{i,t+1} - \mu_{in} + B_{i,t}\right]\right)^{\frac{1}{\nu}} \\ &= \alpha ln w_{n,t} - \alpha ln P_{n,t} - (1-\alpha) ln\left(\frac{(1-\alpha)L_{n,t}}{H_{n,t}}\right) + \nu\left[\frac{1}{\nu}\left(\beta V_{n,t+1} + B_{n,t}\right) - ln\left(m_{nn,t}\right)\right] \\ &= \alpha ln w_{n,t} - \alpha ln P_{n,t} - (1-\alpha) ln\left(\frac{(1-\alpha)L_{n,t}}{H_{n,t}}\right) + \beta V_{n,t+1} + B_{n,t} - \nu ln\left(m_{nn,t}\right) \end{aligned}$$

3. Iterating this equation forward yields:

$$V_{n,t} = \sum_{s=t}^{\infty} \beta^{s-t}\left[\alpha ln w_{n,s} - \alpha ln P_{n,s} - (1-\alpha) ln\left(\frac{(1-\alpha)\, L_{n,s}}{H_{n,s}}\right) + B_{n,s} - \nu ln\left(m_{nn,s}\right)\right]$$

4. Simplifying yields:

$$\begin{aligned} V_{n,t} &= \textstyle\sum_{s=t}^{\infty} \beta^{s-t}\left[\alpha ln w_{n,s} - \alpha ln P_{n,s} - (1-\alpha) ln\left(\frac{(1-\alpha)L_{n,s}}{H_{n,s}}\right) + B_{n,s} - \nu ln\left(m_{nn,s}\right)\right] \\ &= \textstyle\sum_{s=t}^{\infty} \beta^{s-t} ln\left(\frac{w_{n,s}^{\alpha} exp(B_{n,s})}{P_{n,s}^{\alpha}\left(\frac{(1-\alpha)L_{n,s}}{H_{n,s}}\right)^{1-\alpha} m_{nn,s}^{\nu}}\right) \end{aligned}$$

D.5 Derivation of equilibrium condition for lifetime utilities expressed in relative differences

1. From the equilibrium condition for expected lifetime utility in equation (18):

$$\begin{aligned} \left[exp\left(V_{n,t+1} - V_{n,t}\right)\right]^{\frac{1}{\nu}} &= \Big[exp\Big\{\alpha ln w_{n,t+1} - \alpha ln P_{n,t+1} - (1-\alpha) ln\left(\frac{(1-\alpha)L_{n,t+1}}{H_{n,t+1}}\right) \\ &\quad + \nu ln \textstyle\sum_{i\in N}\left(exp\left[\beta V_{i,t+2} - \mu_{in} + B_{i,t+1}\right]\right)^{\frac{1}{\nu}} \\ &\quad - \left(\alpha ln w_{n,t} - \alpha ln P_{n,t} - (1-\alpha) ln\left(\frac{(1-\alpha)L_{n,t}}{H_{n,t}}\right)\right) \\ &\quad - \nu ln \textstyle\sum_{i\in N}\left(exp\left[\beta V_{i,t+1} - \mu_{in} + B_{i,t}\right]\right)^{\frac{1}{\nu}}\Big\}\Big]^{\frac{1}{\nu}} \\ &= \left[\frac{\left(\frac{w_{n,t+1}}{w_{n,t}}\right)^{\alpha}}{\left(\frac{P_{n,t+1}}{P_{n,t}}\right)^{\alpha}\left(\frac{L_{n,t+1}/L_{n,t}}{H_{n,t+1}/H_{n,t}}\right)^{1-\alpha}}\right]^{\frac{1}{\nu}}\left(\frac{\sum_{i\in N}\left(exp\left[\beta V_{i,t+2} - \mu_{in} + B_{i,t+1}\right]\right)^{\frac{1}{\nu}}}{\sum_{i\in N}\left(exp\left[\beta V_{i,t+1} - \mu_{in} + B_{i,t}\right]\right)^{\frac{1}{\nu}}}\right) \end{aligned} \tag{A13}$$

2. Multiplying and dividing each term in the sum $\sum_{i\in N}\left(exp\left[\beta V_{i,t+2} - \mu_{in} + B_{i,t+1}\right]\right)^{\frac{1}{\nu}}$ by $\left(exp\left[\beta V_{i,t+1} - \mu_{in} + B_{i,t}\right]\right)^{\frac{1}{\nu}}$ gives:

$$\begin{aligned} \frac{\sum_{i\in N}\left(exp\left[\beta V_{i,t+2} - \mu_{in} + B_{i,t+1}\right]\right)^{\frac{1}{\nu}}}{\sum_{i\in N}\left(exp\left[\beta V_{i,t+1} - \mu_{in} + B_{i,t}\right]\right)^{\frac{1}{\nu}}} &= \frac{\left(exp\left[\beta V_{1,t+2} - \mu_{1n} + B_{1,t+1}\right]\right)^{\frac{1}{\nu}} + \left(exp\left[\beta V_{2,t+2} - \mu_{2n} + B_{2,t+1}\right]\right)^{\frac{1}{\nu}} + ...}{\sum_{i\in N}\left(exp\left[\beta V_{i,t+1} - \mu_{in} + B_{i,t}\right]\right)^{\frac{1}{\nu}}} \\ &= \frac{\left(exp\left[\beta V_{1,t+2} - \mu_{1n} + B_{1,t+1}\right]\right)^{\frac{1}{\nu}} \frac{\left(exp\left[\beta V_{1,t+1} - \mu_{1n} + B_{1,t}\right]\right)^{\frac{1}{\nu}}}{\left(exp\left[\beta V_{1,t+1} - \mu_{1n} + B_{1,t}\right]\right)^{\frac{1}{\nu}}}}{\sum_{i\in N}\left(exp\left[\beta V_{i,t+1} - \mu_{in} + B_{i,t}\right]\right)^{\frac{1}{\nu}}} \\ &\quad + \frac{\left(exp\left[\beta V_{2,t+2} - \mu_{2n} + B_{2,t+1}\right]\right)^{\frac{1}{\nu}} \frac{\left(exp\left[\beta V_{2,t+1} - \mu_{2n} + B_{2,t}\right]\right)^{\frac{1}{\nu}}}{\left(exp\left[\beta V_{2,t+1} - \mu_{2n} + B_{2,t}\right]\right)^{\frac{1}{\nu}}}}{\sum_{i\in N}\left(exp\left[\beta V_{i,t+1} - \mu_{in} + B_{i,t}\right]\right)^{\frac{1}{\nu}}} + ... \end{aligned}$$

3. Substituting the migration shares equation $m_{in,t} = \frac{(exp[\beta V_{i,t+1} - \mu_{in} + B_{i,t}])^{\frac{1}{\nu}}}{\sum_{m \in N}(exp[\beta V_{m,t+1} - \mu_{mn} + B_{m,t}])^{\frac{1}{\nu}}}$ gives:

$$\begin{aligned}
\frac{\sum_{i \in N}(exp[\beta V_{i,t+2} - \mu_{in} + B_{i,t+1}])^{\frac{1}{\nu}}}{\sum_{i \in N}(exp[\beta V_{i,t+1} - \mu_{in} + B_{i,t}])^{\frac{1}{\nu}}} &= m_{1n,t}\frac{(exp[\beta V_{1,t+2} - \mu_{1n} + B_{1,t+1}])^{\frac{1}{\nu}}}{(exp[\beta V_{1,t+1} - \mu_{1n} + B_{1,t}])^{\frac{1}{\nu}}} + m_{2n,t}\frac{(exp[\beta V_{2,t+2} - \mu_{2n} + B_{2,t+1}])^{\frac{1}{\nu}}}{(exp[\beta V_{2,t+1} - \mu_{2n} + B_{2,t}])^{\frac{1}{\nu}}} + ... \\
&= \sum_{k \in N} m_{kn,t}\frac{\left(exp\left[\beta V_{k,t+2} - \mu_{kn} + B_{k,t+1}\right]\right)^{\frac{1}{\nu}}}{\left(exp\left[\beta V_{k,t+1} - \mu_{kn} + B_{k,t}\right]\right)^{\frac{1}{\nu}}} \\
&= \sum_{k \in N} m_{kn,t}\left(exp\left[\beta\left(V_{k,t+2} - V_{k,t+1}\right) + B_{k,t+1} - B_{k,t}\right]\right)^{\frac{1}{\nu}} \\
&= \sum_{k \in N} m_{kn,t} exp\left[\frac{\beta}{\nu}\left(V_{k,t+2} - V_{k,t+1}\right)\right] exp\left[\frac{1}{\nu}\left(B_{k,t+1} - B_{k,t}\right)\right]
\end{aligned}$$

4. Substituting this back into equation (A13) gives:

$$\begin{aligned}
\left[exp\left(V_{n,t+1} - V_{n,t}\right)\right]^{\frac{1}{\nu}} &= \left[\frac{\left(\frac{w_{n,t+1}}{w_{n,t}}\right)^{\alpha}}{\left(\frac{P_{n,t+1}}{P_{n,t}}\right)^{\alpha}\left(\frac{L_{n,t+1}/L_{n,t}}{H_{n,t+1}/H_{n,t}}\right)^{1-\alpha}}\right]^{\frac{1}{\nu}} \\
&\times \sum_{k \in N} m_{kn,t} exp\left[\frac{\beta}{\nu}\left(V_{k,t+2} - V_{k,t+1}\right)\right] exp\left[\frac{1}{\nu}\left(B_{k,t+1} - B_{k,t}\right)\right]
\end{aligned}$$

5. Defining $Y_{n,t+1} = \left[exp\left(V_{n,t+1} - V_{n,t}\right)\right]^{\frac{1}{\nu}}$ and substituting gives:

$$Y_{n,t+1} = \left[\frac{\left(\frac{w_{n,t+1}}{w_{n,t}}\right)^{\alpha}}{\left(\frac{P_{n,t+1}}{P_{n,t}}\right)^{\alpha}\left(\frac{L_{n,t+1}/L_{n,t}}{H_{n,t+1}/H_{n,t}}\right)^{1-\alpha}}\right]^{\frac{1}{\nu}} \sum_{k \in N} m_{kn,t}\left(Y_{k,t+2}\right)^{\beta} exp\left[\frac{1}{\nu}\left(B_{k,t+1} - B_{k,t}\right)\right]$$

6. The central estimates assume that local amenities are exogenous and time-invariant, $B_{n,t} = B_n$, so this equation reduces to:

$$Y_{n,t+1} = \left[\frac{\left(\frac{w_{n,t+1}}{w_{n,t}}\right)^{\alpha}}{\left(\frac{P_{n,t+1}}{P_{n,t}}\right)^{\alpha}\left(\frac{L_{n,t+1}/L_{n,t}}{H_{n,t+1}/H_{n,t}}\right)^{1-\alpha}}\right]^{\frac{1}{\nu}} \sum_{k \in N} m_{kn,t}\left(Y_{k,t+2}\right)^{\beta} \qquad \text{(A14)}$$

D.6 Derivation of equilibrium condition for migration shares expressed in relative differences

1. From the equilibrium condition for migration shares in equation (19):

$$\begin{aligned}
\frac{m_{in,t+1}}{m_{in,t}} &= \frac{(exp[\beta V_{i,t+2}-\mu_{in}+B_{i,t+1}])^{\frac{1}{\nu}}}{\sum_{k\in N}\left(exp\left[\beta V_{k,t+2}-\mu_{kn}+B_{k,t+1}\right]\right)^{\frac{1}{\nu}}} \Big/ \frac{(exp[\beta V_{i,t+1}-\mu_{in}+B_{i,t}])^{\frac{1}{\nu}}}{\sum_{k\in N}\left(exp\left[\beta V_{k,t+1}-\mu_{kn}+B_{k,t}\right]\right)^{\frac{1}{\nu}}} \\
&= \frac{(exp[\beta V_{i,t+2}+B_{i,t+1}-\beta V_{i,t+1}-B_{i,t}])^{\frac{1}{\nu}}}{\sum_{k\in N}\left(exp\left[\beta V_{k,t+2}-\mu_{kn}+B_{k,t+1}\right]\right)^{\frac{1}{\nu}} / \sum_{k\in N}\left(exp\left[\beta V_{k,t+1}-\mu_{kn}+B_{k,t}\right]\right)^{\frac{1}{\nu}}} \\
&= \frac{(exp[\beta V_{i,t+2}+B_{i,t+1}-\beta V_{i,t+1}-B_{i,t}])^{\frac{1}{\nu}}}{\left\{\frac{\sum_{k\in N}\left(exp\left[\beta V_{k,t+2}-\mu_{kn}+B_{k,t+1}\right]\right)^{\frac{1}{\nu}}\times\frac{\left(exp\left[\beta V_{k,t+1}-\mu_{kn}+B_{k,t}\right]\right)^{\frac{1}{\nu}}}{\left(exp\left[\beta V_{k,t+1}-\mu_{kn}+B_{k,t}\right]\right)^{\frac{1}{\nu}}}}{\sum_{k\in N}\left(exp\left[\beta V_{k,t+1}-\mu_{kn}+B_{k,t}\right]\right)^{\frac{1}{\nu}}}\right\}} \\
&= \frac{(exp[\beta V_{i,t+2}+B_{i,t+1}-\beta V_{i,t+1}-B_{i,t}])^{\frac{1}{\nu}}}{\sum_{k\in N} m_{kn,t}\left(exp\left[\beta V_{k,t+2}+B_{k,t+1}-\beta V_{k,t+1}-B_{k,t}\right]\right)^{\frac{1}{\nu}}} \\
&= \frac{(exp[\beta(V_{i,t+2}-V_{i,t+1})]exp[B_{i,t+1}-B_{i,t}])^{\frac{1}{\nu}}}{\sum_{k\in N} m_{kn,t}\left(exp\left[\beta\left(V_{k,t+2}-V_{k,t+1}\right)\right]exp\left[B_{k,t+1}-B_{k,t}\right]\right)^{\frac{1}{\nu}}}
\end{aligned}$$

2. Defining $Y_{n,t+1} = [exp\,(V_{n,t+1} - V_{n,t})]^{\frac{1}{\nu}}$ and substituting gives:

$$\frac{m_{in,t+1}}{m_{in,t}} = \frac{(Y_{i,t+2})^{\beta}(exp[B_{i,t+1}-B_{i,t}])^{\frac{1}{\nu}}}{\sum_{k\in N} m_{kn,t}\left(Y_{k,t+2}\right)^{\beta}\left(exp\left[B_{k,t+1}-B_{k,t}\right]\right)^{\frac{1}{\nu}}}$$

3. The central estimates assume that local amenities are exogenous and time-invariant, $B_{n,t} = B_n$, so this equation reduces to:

$$\frac{m_{in,t+1}}{m_{in,t}} = \frac{(Y_{i,t+2})^{\beta}}{\sum_{k\in N} m_{kn,t}\left(Y_{k,t+2}\right)^{\beta}} \tag{A15}$$

D.7 Derivation of welfare change induced by changes in the economy's fundamentals (Equation (24))

Denoting by $\widehat{x}$ the value of a variable x under an alternative scenario for the economy's fundamentals, welfare in location n at time t with and without the change in fundamentals are given by, respectively:

$$\widehat{W_{n,t}} = \sum_{s=t}^{\infty}\beta^{s-t}ln\left(\frac{\widehat{w_{n,s}}^{\alpha}exp\left(\widehat{B_{n,s}}\right)}{\widehat{P_{n,s}}^{\alpha}\left(\frac{(1-\alpha)\widehat{L_{n,s}}}{\widehat{H_{n,s}}}\right)^{1-\alpha}\widehat{m_{nn,s}}^{\nu}}\right)$$

and:

$$W_{n,t} = \sum_{s=t}^{\infty}\beta^{s-t}ln\left(\frac{w_{n,s}^{\alpha}exp\left(B_{n,s}\right)}{P_{n,s}^{\alpha}\left(\frac{(1-\alpha)L_{n,s}}{H_{n,s}}\right)^{1-\alpha}m_{nn,s}^{\nu}}\right)$$

The compensating variation in consumption for location n at time t is given by $\delta_{n,t}$ such that:

$$\widehat{W_{n,t}} = \sum_{s=t}^{\infty} \beta^{s-t} ln \left(\frac{\delta_{n,t} w_{n,s}^{\alpha} exp\left(B_{n,s}\right)}{P_{n,s}^{\alpha} \left(\frac{(1-\alpha)L_{n,s}}{H_{n,s}}\right)^{1-\alpha} m_{nn,s}^{\nu}} \right)$$

This yields an expression for the consumption equivalent change in welfare:

$$\triangle Welfare_{n,t} = ln\left(\delta_{n,t}\right) = (1-\beta) \sum_{s=t}^{\infty} \beta^{s-t} ln \left(\frac{\left(\frac{\widehat{w_{n,s}}}{w_{n,s}}\right)^{\alpha} \frac{exp\left(\widehat{B_{n,s}}\right)}{exp(B_{n,s})}}{\left(\frac{\widehat{P_{n,s}}}{P_{n,s}}\right)^{\alpha} \left(\frac{\widehat{L_{n,s}}/L_{n,s}}{\widehat{H_{n,s}}/H_{n,s}}\right)^{1-\alpha} \left(\frac{\widehat{m_{nn,s}}}{m_{nn,s}}\right)^{\nu}} \right)$$

The aggregate welfare change is obtained by taking the mean value across locations, weighted by their respective initial population shares:

$$\triangle Welfare_{t} = \sum_{n \in N} \frac{L_{n,0}}{\sum_{i \in N} L_{i,0}} \left\{ (1-\beta) \sum_{s=t}^{\infty} \beta^{s-t} ln \left(\frac{\left(\frac{\widehat{w_{n,s}}}{w_{n,s}}\right)^{\alpha} \frac{exp\left(\widehat{B_{n,s}}\right)}{exp(B_{n,s})}}{\left(\frac{\widehat{P_{n,s}}}{P_{n,s}}\right)^{\alpha} \left(\frac{\widehat{L_{n,s}}/L_{n,s}}{\widehat{H_{n,s}}/H_{n,s}}\right)^{1-\alpha} \left(\frac{\widehat{m_{nn,s}}}{m_{nn,s}}\right)^{\nu}} \right) \right\} \quad \text{(A16)}$$

D.8 Derivation of equilibrium conditions for lifetime utilities, migration shares and population with unanticipated sea level rise (Equations (A3) to (A6))

1. The assumption made about how agents anticipate the evolution of the future path of sea level rise is as follows. At $t = 0$ (2010), agents expect gradual inundation over the periods $t = 1$ to $t = 9$, with sea levels maintained at their $t = 9$ levels thereafter. At $t = 10$, agents learn that the gradual inundation will continue until $t = 20$ (2110), after which sea levels remain constant. Let $X\left(\Theta^{s}\right)$ denote the variable X according to the information available in period s.

2. Using the equilibrium conditions in relative time differences for expected lifetime utility in equation (A14) and for migration shares in equation (A15), the evolution of $\left\{ m\left(\Theta^{0}\right)_{ni,t}, Y\left(\Theta^{0}\right)_{n,t+1} \right\}_{t=0}^{\infty}$ in the absence of any shocks can be obtained from:

$$Y\left(\Theta^{0}\right)_{n,t+1} = \left[\frac{\left(\frac{w\left(\Theta^{0}\right)_{n,t+1}}{w\left(\Theta^{0}\right)_{n,t}}\right)^{\alpha}}{\left(\frac{P\left(\Theta^{0}\right)_{n,t+1}}{P\left(\Theta^{0}\right)_{n,t}}\right)^{\alpha} \left(\frac{L\left(\Theta^{0}\right)_{n,t+1}/L\left(\Theta^{0}\right)_{n,t}}{H\left(\Theta^{0}\right)_{n,t+1}/H\left(\Theta^{0}\right)_{n,t}}\right)^{1-\alpha}} \right]^{\frac{1}{\nu}} \times \sum_{k \in N} m\left(\Theta^{0}\right)_{kn,t} \left(Y\left(\Theta^{0}\right)_{k,t+2}\right)^{\beta} exp\left[\frac{1}{\nu}\left(B\left(\Theta^{0}\right)_{k,t+1} - B\left(\Theta^{0}\right)_{k,t}\right)\right]$$

$$\frac{m\left(\Theta^{0}\right)_{in,t+1}}{m\left(\Theta^{0}\right)_{in,t}} = \frac{\left(Y\left(\Theta^{0}\right)_{i,t+2}\right)^{\beta} \left(exp\left[B\left(\Theta^{0}\right)_{i,t+1} - B\left(\Theta^{0}\right)_{i,t}\right]\right)^{\frac{1}{\nu}}}{\sum_{k \in N} m\left(\Theta^{0}\right)_{kn,t} \left(Y\left(\Theta^{0}\right)_{k,t+2}\right)^{\beta} \left(exp\left[B\left(\Theta^{0}\right)_{k,t+1} - B\left(\Theta^{0}\right)_{k,t}\right]\right)^{\frac{1}{\nu}}}$$

3. No shocks occur during $0 \leq t \leq 9$. At $t = 10$, the shock is received and the information set

$\left(\Theta^{10}\right)$ becomes available. Adding and subtracting $\beta V\left(\Theta^{10}\right)_{i,10}$ in the equations for $V\left(\Theta^{0}\right)_{i,9}$ and $m\left(\Theta^{0}\right)_{in,9}$ yields:

$$\begin{aligned} V\left(\Theta^{0}\right)_{n,9} \quad = \quad & \alpha lnw\left(\Theta^{0}\right)_{n,9} - \alpha lnP\left(\Theta^{0}\right)_{n,9} - (1-\alpha)ln\left(\frac{(1-\alpha)L\left(\Theta^{0}\right)_{n,9}}{H(\Theta^{0})_{n,9}}\right) + \\ & \nu ln \textstyle\sum_{i\in N}\left(exp\left[V\left(\Theta^{0}\right)_{i,10} - V\left(\Theta^{10}\right)_{i,10}\right]\right)^{\frac{\beta}{\nu}}\left(exp\left[\beta V\left(\Theta^{10}\right)_{i,10} - \mu_{in} + B\left(\Theta^{0}\right)_{i,9}\right]\right)^{\frac{1}{\nu}} \end{aligned}$$

$$m\left(\Theta^{0}\right)_{in,9} = \frac{\left(exp\left[V\left(\Theta^{0}\right)_{i,10} - V\left(\Theta^{10}\right)_{i,10}\right]\right)^{\frac{\beta}{\nu}}\left(exp\left[\beta V\left(\Theta^{10}\right)_{i,10} - \mu_{in} + B\left(\Theta^{0}\right)_{i,9}\right]\right)^{\frac{1}{\nu}}}{\sum_{k\in N}\left(exp\left[V\left(\Theta^{0}\right)_{k,10} - V\left(\Theta^{10}\right)_{k,10}\right]\right)^{\frac{\beta}{\nu}}\left(exp\left[\beta V\left(\Theta^{10}\right)_{k,10} - \mu_{kn} + B\left(\Theta^{0}\right)_{k,9}\right]\right)^{\frac{1}{\nu}}} \tag{A17}$$

4. Based on the new information that becomes available with the shock at $t = 10$, in periods thereafter:

$$\begin{aligned} V\left(\Theta^{10}\right)_{n,t} \quad = \quad & \alpha lnw\left(\Theta^{10}\right)_{n,t} - \alpha lnP\left(\Theta^{10}\right)_{n,t} - (1-\alpha)ln\left(\frac{(1-\alpha)L\left(\Theta^{10}\right)_{n,t}}{H(\Theta^{10})_{n,t}}\right) \\ & + \nu ln \textstyle\sum_{i\in N}\left(exp\left[\beta V\left(\Theta^{10}\right)_{i,t+1} - \mu_{in} + B\left(\Theta^{10}\right)_{i,t}\right]\right)^{\frac{1}{\nu}} \end{aligned}$$

$$m\left(\Theta^{10}\right)_{in,t} = \frac{\left(exp\left[\beta V\left(\Theta^{10}\right)_{i,t+1} - \mu_{in} + B\left(\Theta^{10}\right)_{i,t}\right]\right)^{\frac{1}{\nu}}}{\sum_{k\in N}\left(exp\left[\beta V\left(\Theta^{10}\right)_{k,t+1} - \mu_{kn} + B\left(\Theta^{10}\right)_{k,t}\right]\right)^{\frac{1}{\nu}}} \tag{A18}$$

5. Taking the difference between $V\left(\Theta^{10}\right)_{n,10}$ and $V\left(\Theta^{0}\right)_{n,9}$ gives:

$$\begin{aligned}
V\left(\Theta^{10}\right)_{n,10}-V\left(\Theta^{0}\right)_{n,9} &= \alpha lnw\left(\Theta^{10}\right)_{n,10}-\alpha lnP\left(\Theta^{10}\right)_{n,10}-(1-\alpha)ln\left(\frac{(1-\alpha)L\left(\Theta^{10}\right)_{n,10}}{H(\Theta^{10})_{n,10}}\right)\\
&\quad-\left[\alpha lnw\left(\Theta^{0}\right)_{n,9}-\alpha lnP\left(\Theta^{0}\right)_{n,9}-(1-\alpha)ln\left(\frac{(1-\alpha)L\left(\Theta^{0}\right)_{n,9}}{H(\Theta^{0})_{n,9}}\right)\right]\\
&\quad+\nu ln\sum_{i\in N}\left(exp\left[\beta V\left(\Theta^{10}\right)_{i,11}-\mu_{in}+B\left(\Theta^{10}\right)_{i,10}\right]\right)^{\frac{1}{\nu}}\\
&\quad-\nu ln\sum_{i\in N}\left(exp\left[V\left(\Theta^{0}\right)_{i,10}-V\left(\Theta^{10}\right)_{i,10}\right]\right)^{\frac{\beta}{\nu}}\\
&\quad\times\left(exp\left[\beta V\left(\Theta^{10}\right)_{i,10}-\mu_{in}+B\left(\Theta^{0}\right)_{i,9}\right]\right)^{\frac{1}{\nu}}\\
&= ln\left[\frac{\left(\frac{w\left(\Theta^{10}\right)_{n,10}}{w(\Theta^{0})_{n,9}}\right)^{\alpha}}{\left(\frac{P\left(\Theta^{10}\right)_{n,10}}{P\left(\Theta^{0}\right)_{n,9}}\right)^{\alpha}\left(\frac{L\left(\Theta^{10}\right)_{n,10}/L\left(\Theta^{0}\right)_{n,9}}{H(\Theta^{10})_{n,10}/H(\Theta^{0})_{n,9}}\right)^{1-\alpha}}\right]\\
&\quad+\nu ln\left(\frac{\sum_{i\in N}\left(exp\left[\beta V\left(\Theta^{10}\right)_{i,11}-\mu_{in}+B\left(\Theta^{10}\right)_{i,10}\right]\right)^{\frac{1}{\nu}}}{\sum_{i\in N}\left(exp\left[V(\Theta^{0})_{i,10}-V(\Theta^{10})_{i,10}\right]\right)^{\frac{\beta}{\nu}}\left(exp\left[\beta V(\Theta^{10})_{i,10}-\mu_{in}+B(\Theta^{0})_{i,9}\right]\right)^{\frac{1}{\nu}}}\right)\\
&= ln\left[\frac{\left(\frac{w\left(\Theta^{10}\right)_{n,10}}{w(\Theta^{0})_{n,9}}\right)^{\alpha}}{\left(\frac{P\left(\Theta^{10}\right)_{n,10}}{P\left(\Theta^{0}\right)_{n,9}}\right)^{\alpha}\left(\frac{L\left(\Theta^{10}\right)_{n,10}/L\left(\Theta^{0}\right)_{n,9}}{H(\Theta^{10})_{n,10}/H(\Theta^{0})_{n,9}}\right)^{1-\alpha}}\right]\\
&\quad+ln\left(\sum_{i\in N}\frac{m\left(\Theta^{0}\right)_{in,9}\left(exp\left[\beta V\left(\Theta^{10}\right)_{i,11}-\beta V\left(\Theta^{10}\right)_{i,10}+B\left(\Theta^{10}\right)_{i,10}-B\left(\Theta^{0}\right)_{i,9}\right]\right)^{\frac{1}{\nu}}}{\left(exp\left[V(\Theta^{0})_{i,10}-V(\Theta^{10})_{i,10}\right]\right)^{\frac{\beta}{\nu}}}\right)^{\nu}
\end{aligned}$$

6. Exponentiating and substituting $Y\left(\Theta^{10}\right)_{n,10}=\left[exp\left(V\left(\Theta^{10}\right)_{n,10}-V\left(\Theta^{0}\right)_{n,9}\right)\right]^{\frac{1}{\nu}}$,
$Y\left(\Theta^{0}\right)_{n,10}=\left[exp\left(V\left(\Theta^{0}\right)_{n,10}-V\left(\Theta^{0}\right)_{n,9}\right)\right]^{\frac{1}{\nu}}$ and $Y\left(\Theta^{10}\right)_{n,t+1}=\left[exp\left(V\left(\Theta^{10}\right)_{n,t+1}-V\left(\Theta^{10}\right)_{n,t}\right)\right]^{\frac{1}{\nu}}$:

$$\begin{aligned}
Y\left(\Theta^{10}\right)_{n,10} &= \left[exp\left(V\left(\Theta^{10}\right)_{n,10}-V\left(\Theta^{0}\right)_{n,9}\right)\right]^{\frac{1}{\nu}}\\
&= \left[\frac{\left(\frac{w\left(\Theta^{10}\right)_{n,10}}{w(\Theta^{0})_{n,9}}\right)^{\alpha}}{\left(\frac{P\left(\Theta^{10}\right)_{n,10}}{P\left(\Theta^{0}\right)_{n,9}}\right)^{\alpha}\left(\frac{L\left(\Theta^{10}\right)_{n,10}/L\left(\Theta^{0}\right)_{n,9}}{H(\Theta^{10})_{n,10}/H(\Theta^{0})_{n,9}}\right)^{1-\alpha}}\right]^{\frac{1}{\nu}}\\
&= \times\sum_{i\in N}\frac{m\left(\Theta^{0}\right)_{in,9}\left(exp\left[V\left(\Theta^{10}\right)_{i,11}-V\left(\Theta^{10}\right)_{i,10}\right]\right)^{\frac{\beta}{\nu}}\left(exp\left[B\left(\Theta^{10}\right)_{i,10}-B\left(\Theta^{0}\right)_{i,9}\right]\right)^{\frac{1}{\nu}}}{\left(exp\left[V(\Theta^{0})_{i,10}-V(\Theta^{10})_{i,10}\right]\right)^{\frac{\beta}{\nu}}}\\
&= \left[\frac{\left(\frac{w\left(\Theta^{10}\right)_{n,10}}{w(\Theta^{0})_{n,9}}\right)^{\alpha}}{\left(\frac{P\left(\Theta^{10}\right)_{n,10}}{P\left(\Theta^{0}\right)_{n,9}}\right)^{\alpha}\left(\frac{L\left(\Theta^{10}\right)_{n,10}/L\left(\Theta^{0}\right)_{n,9}}{H(\Theta^{10})_{n,10}/H(\Theta^{0})_{n,9}}\right)^{1-\alpha}}\right]^{\frac{1}{\nu}}\\
&\quad\times\sum_{i\in N}\frac{m\left(\Theta^{0}\right)_{in,9}\left(Y\left(\Theta^{10}\right)_{i,11}\right)^{\beta}\left(exp\left[B\left(\Theta^{10}\right)_{i,10}-B\left(\Theta^{0}\right)_{i,9}\right]\right)^{\frac{1}{\nu}}}{\left(exp\left[V(\Theta^{0})_{i,10}-V(\Theta^{0})_{i,9}+V(\Theta^{0})_{i,9}-V(\Theta^{10})_{i,10}\right]\right)^{\frac{\beta}{\nu}}}\\
&= \left[\frac{\left(\frac{w\left(\Theta^{10}\right)_{n,10}}{w(\Theta^{0})_{n,9}}\right)^{\alpha}}{\left(\frac{P\left(\Theta^{10}\right)_{n,10}}{P\left(\Theta^{0}\right)_{n,9}}\right)^{\alpha}\left(\frac{L\left(\Theta^{10}\right)_{n,10}/L\left(\Theta^{0}\right)_{n,9}}{H(\Theta^{10})_{n,10}/H(\Theta^{0})_{n,9}}\right)^{1-\alpha}}\right]^{\frac{1}{\nu}}\\
&\quad\times\sum_{i\in N}\left(\frac{Y\left(\Theta^{10}\right)_{i,10}}{Y\left(\Theta^{0}\right)_{i,10}}\right)^{\beta}m\left(\Theta^{0}\right)_{in,9}\left(Y\left(\Theta^{10}\right)_{i,11}\right)^{\beta}\left(exp\left[B\left(\Theta^{10}\right)_{i,10}-B\left(\Theta^{0}\right)_{i,9}\right]\right)^{\frac{1}{\nu}}
\end{aligned}$$

7. Taking equation (A18) for $m\left(\Theta^5\right)_{in,10}$ and dividing by the expression for $m\left(\Theta^0\right)_{in,9}$ in equation (A17) yields:

$$\frac{m(\Theta^{10})_{in,10}}{m(\Theta^0)_{in,9}} = \frac{\frac{\left(exp\left[\beta V\left(\Theta^{10}\right)_{i,11}-\mu_{in}+B\left(\Theta^{10}\right)_{i,10}\right]\right)^{\frac{1}{\nu}}}{\sum_{k\in N}\left(exp\left[\beta V(\Theta^{10})_{k,11}-\mu_{kn}+B(\Theta^{10})_{k,10}\right]\right)^{\frac{1}{\nu}}}}{\frac{\left(exp\left[V(\Theta^0)_{i,10}-V(\Theta^{10})_{i,10}\right]\right)^{\frac{\beta}{\nu}}\left(exp\left[\beta V(\Theta^{10})_{i,10}-\mu_{in}+B(\Theta^0)_{i,9}\right]\right)^{\frac{1}{\nu}}}{\sum_{k\in N}\left(exp\left[V(\Theta^0)_{k,10}-V(\Theta^{10})_{k,10}\right]\right)^{\frac{\beta}{\nu}}\left(exp\left[\beta V(\Theta^{10})_{k,10}-\mu_{kn}+B(\Theta^0)_{k,9}\right]\right)^{\frac{1}{\nu}}}}$$

$$= \frac{\left(Y\left(\Theta^{10}\right)_{i,11}\right)^{\beta}\left(\frac{Y\left(\Theta^{10}\right)_{i,10}}{Y\left(\Theta^{0}\right)_{i,10}}\right)^{\beta}\left(exp\left[B\left(\Theta^{10}\right)_{i,10}-B\left(\Theta^{0}\right)_{i,9}\right]\right)^{\frac{1}{\nu}}}{\sum_{k\in N} m(\Theta^0)_{kn,9}\left(Y(\Theta^{10})_{k,11}\right)^{\beta}\left(\frac{Y(\Theta^{10})_{k,10}}{Y(\Theta^0)_{k,10}}\right)^{\beta}\left(exp\left[B(\Theta^{10})_{k,10}-B(\Theta^0)_{k,9}\right]\right)^{\frac{1}{\nu}}}$$

8. In time periods after $t=10$, the same method as was used to prove equations (A14) and (A15) can be used to show that:

$$Y\left(\Theta^{10}\right)_{n,t+1} = \left[\frac{\left(\frac{w\left(\Theta^{10}\right)_{n,t+1}}{w(\Theta^{10})_{n,t}}\right)^{\alpha}}{\left(\frac{P(\Theta^{10})_{n,t+1}}{P(\Theta^{10})_{n,t}}\right)^{\alpha}\left(\frac{L(\Theta^{10})_{n,t+1}/L(\Theta^{10})_{n,t}}{H(\Theta^{10})_{n,t+1}/H(\Theta^{10})_{n,t}}\right)^{1-\alpha}}\right]^{\frac{1}{\nu}}$$
$$\times \sum_{k\in N} m\left(\Theta^{10}\right)_{kn,t}\left(Y\left(\Theta^{10}\right)_{k,t+2}\right)^{\beta}\left(exp\left[B\left(\Theta^{10}\right)_{i,t+1}-B\left(\Theta^{10}\right)_{i,t}\right]\right)^{\frac{1}{\nu}}, \quad t\geq 10$$

and:

$$\frac{m\left(\Theta^{10}\right)_{in,t+1}}{m\left(\Theta^{10}\right)_{in,t}} = \frac{\left(Y\left(\Theta^{10}\right)_{i,t+2}\right)^{\beta}\left(exp\left[B\left(\Theta^{10}\right)_{i,t+1}-B\left(\Theta^{10}\right)_{i,t}\right]\right)^{\frac{1}{\nu}}}{\sum_{k\in N} m\left(\Theta^{10}\right)_{kn,t}\left(Y\left(\Theta^{10}\right)_{k,t+2}\right)^{\beta}\left(exp\left[B\left(\Theta^{10}\right)_{k,t+1}-B\left(\Theta^{10}\right)_{k,t}\right]\right)^{\frac{1}{\nu}}}$$

9. In the general case, for time periods $\tilde{t}$ in which shocks arrive:

$$Y\left(\Theta^{\tilde{t}}\right)_{n,\tilde{t}} = \left[\frac{\left(\frac{w\left(\Theta^{\tilde{t}}\right)_{n,\tilde{t}}}{w\left(\Theta^{\tilde{t}-1}\right)_{n,\tilde{t}-1}}\right)^{\alpha}}{\left(\frac{P\left(\Theta^{\tilde{t}}\right)_{n,\tilde{t}}}{P\left(\Theta^{\tilde{t}-1}\right)_{n,\tilde{t}-1}}\right)^{\alpha}\left(\frac{L\left(\Theta^{\tilde{t}}\right)_{n,\tilde{t}}/L\left(\Theta^{\tilde{t}-1}\right)_{n,\tilde{t}-1}}{H\left(\Theta^{\tilde{t}}\right)_{n,\tilde{t}}/H\left(\Theta^{\tilde{t}-1}\right)_{n,\tilde{t}-1}}\right)^{1-\alpha}}\right]^{\frac{1}{\nu}}$$
$$\times \sum_{i\in N}\left(\frac{Y\left(\Theta^{\tilde{t}}\right)_{i,\tilde{t}}}{Y\left(\Theta^{\tilde{t}-1}\right)_{i,\tilde{t}}}\right)^{\beta} m\left(\Theta^{\tilde{t}-1}\right)_{in,\tilde{t}-1}\left(Y\left(\Theta^{\tilde{t}}\right)_{i,\tilde{t}+1}\right)^{\beta}$$
$$\times \left(exp\left[B\left(\Theta^{\tilde{t}}\right)_{i,\tilde{t}}-B\left(\Theta^{\tilde{t}-1}\right)_{i,\tilde{t}-1}\right]\right)^{\frac{1}{\nu}}$$

$$Y\left(\Theta^{\tilde{t}}\right)_{n,t+1} = \left[\frac{\left(\frac{w\left(\Theta^{\tilde{t}}\right)_{n,t+1}}{w\left(\Theta^{\tilde{t}}\right)_{n,t}}\right)^{\alpha}}{\left(\frac{P\left(\Theta^{\tilde{t}}\right)_{n,t+1}}{P\left(\Theta^{\tilde{t}}\right)_{n,t}}\right)^{\alpha}\left(\frac{L\left(\Theta^{\tilde{t}}\right)_{n,t+1}/L\left(\Theta^{\tilde{t}}\right)_{n,t}}{H\left(\Theta^{\tilde{t}}\right)_{n,t+1}/H\left(\Theta^{\tilde{t}}\right)_{n,t}}\right)^{1-\alpha}}\right]^{\frac{1}{\nu}}$$
$$\times \sum_{k\in N} m\left(\Theta^{\tilde{t}}\right)_{kn,t}\left(Y\left(\Theta^{\tilde{t}}\right)_{k,t+2}\right)^{\beta}\left(exp\left[B\left(\Theta^{\tilde{t}}\right)_{i,t+1}-B\left(\Theta^{\tilde{t}}\right)_{i,t}\right]\right)^{\frac{1}{\nu}}, \quad t\geq\tilde{t}$$

and:

$$\frac{m\left(\Theta^{\tilde{t}}\right)_{in,\tilde{t}}}{m\left(\Theta^{\tilde{t}-1}\right)_{in,\tilde{t}-1}} = \frac{\left(Y\left(\Theta^{\tilde{t}}\right)_{i,\tilde{t}+1}\right)^{\beta}\left(\frac{Y\left(\Theta^{\tilde{t}}\right)_{i,\tilde{t}}}{Y\left(\Theta^{\tilde{t}-1}\right)_{i,\tilde{t}}}\right)^{\beta}\left(exp\left[B\left(\Theta^{\tilde{t}}\right)_{i,\tilde{t}}-B\left(\Theta^{\tilde{t}-1}\right)_{i,\tilde{t}-1}\right]\right)^{\frac{1}{\nu}}}{\sum_{k\in N} m\left(\Theta^{\tilde{t}-1}\right)_{kn,\tilde{t}-1}\left(Y\left(\Theta^{\tilde{t}}\right)_{k,\tilde{t}+1}\right)^{\beta}\left(\frac{Y\left(\Theta^{\tilde{t}}\right)_{k,\tilde{t}}}{Y\left(\Theta^{\tilde{t}-1}\right)_{k,\tilde{t}}}\right)^{\beta}\left(exp\left[B\left(\Theta^{\tilde{t}}\right)_{k,\tilde{t}}-B\left(\Theta^{\tilde{t}-1}\right)_{k,\tilde{t}-1}\right]\right)^{\frac{1}{\nu}}}$$

$$\frac{m\left(\Theta^{\tilde{t}}\right)_{in,t+1}}{m\left(\Theta^{\tilde{t}}\right)_{in,t}} = \frac{\left(Y\left(\Theta^{\tilde{t}}\right)_{i,t+2}\right)^{\beta}\left(exp\left[B\left(\Theta^{\tilde{t}}\right)_{i,t+1}-B\left(\Theta^{\tilde{t}}\right)_{i,t}\right]\right)^{\frac{1}{\nu}}}{\sum_{k\in N} m\left(\Theta^{\tilde{t}}\right)_{kn,t}\left(Y\left(\Theta^{\tilde{t}}\right)_{k,t+2}\right)^{\beta}\left(exp\left[B\left(\Theta^{\tilde{t}}\right)_{k,t+1}-B\left(\Theta^{\tilde{t}}\right)_{k,t}\right]\right)^{\frac{1}{\nu}}}, \quad t \geq \tilde{t}$$