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

Clare Balboni *

**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.

**JEL codes**: J61, O18, O53, Q54, R11, R12, R13, R42

**Keywords**: Transport infrastructure, regional development, natural disaster risk, climate change, path dependence, spatial misallocation, sea level, floods, Vietnam

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* Department of Economics, London School of Economics and Political Science. Email: c.a.balboni@lse.ac.uk. I thank Oriana Bandiera, Gharad Bryan, Robin Burgess, Vernon Henderson and Daniel Sturm for their continuous guidance and support on this project. I also thank David Atkin, Tim Besley, Francesco Caselli, Dave Donaldson, Liran Einav, Andreas Ek, Benjamin Faber, Doug Gollin, Du Huynh, Guy Michaels, Benjamin Moll, Melanie Morten, David Nagy, Benjamin Olken, Stephen Redding, Matthew Turner, four anonymous referees and seminar audiences at many institutions for comments that have improved this work. Aaron Berman, Helen Gu, Lindsey Gambino, Thuy (Peter) Le, Sidharth Moktan, Victor Quintas-Martinez and Yifan Wang provided outstanding research assistance. I am grateful to Luis Blancas, Quoc-Anh Do, Kieu-Trang Nguyen and Nguyen Viet Cuong for sharing data. I gratefully acknowledge financial support from the Economic and Social Research Council and the Global Research Program on Spatial Development of Cities, funded by the Multi Donor Trust Fund on Sustainable Urbanization of the World Bank and supported by the UK Department for International Development.

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), Fajgelbaum and Schaal (2020), Allen and Arkolakis (2022)). 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, Chaudhuri, and McLaren (2010) and Caliendo, Dvorkin, and Parro (2019). The production structure builds on seminal models in the new economic geography literature (Krugman (1991b), Helpman (1998), Kucheryavyy, Lyn, and Rodríguez-Clare (2023)), 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, productivities and trade costs as sea level rise takes effect, I then solve the model for each location's equilibrium path of wages and employment. 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 welfare gains, measured in terms of consumption equivalent variation, from realized road upgrades made in Vietnam from 2000 to 2010 would have been 1.73% 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 35% lower at 1.13%. 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 the returns to transport upgrading projects in a range of contexts (e.g. Allen and

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[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.

Arkolakis (2014), Baum-Snow et al. (2018), Alder (2023)), 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 (Fajgelbaum and Schaal (2020), Allen and Arkolakis (2022)) – and approximations of these that policymakers use in practice. 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 allocation rules of the same total cost as the status quo road investments, both with and without accounting for future inundation.

The first set of counterfactuals are based on a simple allocation rule, closely linked to those used by transport planners in practice, and which draws only on data which would have been available in the period in which the allocation decision was made. This allocation rule prioritizes bilateral upgrades between spatial units based on their pairwise market potential in the initial period. The second set of counterfactuals aims to more closely approximate an efficient allocation in a computationally feasible manner, by instead maximizing the welfare contribution of road investments via endogenous improvements in dynamic market access. In both cases, I consider an 'unconstrained' version of the allocation rule which ignores the effects of future inundation, and a 'foresighted' version where the selected routes to upgrade reflect the dynamic impacts of sea level rise.

The second 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 that abstracts from future inundation would suggest that the welfare gains from investment allocations that are not constrained to avoid vulnerable regions exceed those of their foresighted counterparts. In this scenario, the estimated welfare gains relative to the status quo road investments from the counterfactual maximizing unconstrained pairwise market potential (dynamic market access) is 1.03% (1.24%), compared to 0.93% (0.83%) for the allocation based on the same rule avoiding the most vulnerable regions. In contrast, once the effects of future inundation are included in the simulations, the results instead suggest that the 1.30% (1.47%) gains from the foresighted allocation exceed the 1.26% (1.39%) gains from the unconstrained allocation. The concentration of existing economic activity near coasts drives a significant coastal focus among all counterfactual road allocations, constraining the welfare gains available from adjusting transport investment strategies inland when confronted with sea level rise. However, these differences are sizable relative to estimates of the gains from optimal road network reallocation in other settings (Fajgelbaum and Schaal (2020)), and highlight that consideration of future environmental change is central to assessing the returns to, and selecting the efficient allocation of, investments made today.

The higher aggregate long-run welfare gains available from allocations that avoid the most vulnerable regions, relative to otherwise comparable allocations that do not, are 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 pairwise market potential (market access) maximizing allocation dominate gains from its foresighted counterpart when the time horizon considered extends up to 2035 (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 I introduces the quantitative spatial model used to study the effects of road upgrades. Section II 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 III describes the parameterization of the model and calibration of district-level values for relative market access and productivities in an initial period. Section IV 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 V simulates the dynamic welfare gains from a series of counterfactual road investment allocations which anticipate future sea level rise to varying degrees. Section VI concludes.

# I 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 much of the spatial equilibrium literature focuses 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, Chaudhuri, and McLaren (2010) and Caliendo, Dvorkin, and Parro (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, Lyn, and Rodríguez-Clare (2023), 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 is subject to iceberg trade costs which depend on the transport network each period.

## A 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.

## B 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 $\mu_{ni}$, 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 $\eta$ and CES across varieties within a location bundle with

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[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 (2006), Bryan and Morten (2018)), and likely to be so in my empirical setting (Anh (1999)).

elasticity of substitution $\sigma$. The residential land share in consumption expenditure is given by $1-\alpha$.

Following Artuç, Chaudhuri, and McLaren (2010), the idiosyncratic preference shocks $b_{n,t}$ are assumed to follow a Gumbel distribution with parameters $(-\gamma\nu, \nu)$, where $\gamma$ is Euler's constant. Based on this assumption, it is shown in Appendix IV 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 for the next period, where the expectation is over preference shocks:

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

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

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

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:

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

## C 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 $\forall i, n, t$. Trade costs are assumed to be symmetric such that $d_{ni,t} = d_{in,t}$. 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 IV derives the following expressions for the consumption goods price index, $P_{n,t}$ and trade shares $\pi_{ni,t}$:

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

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

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 $t$.

In each location, standard expressions define consumer market access as $CMA_{i,t} = P_{i,t}^{1-\eta}$ and firm market access as $FMA_{i,t} = \sum_{n \in N} \frac{X_{n,t}}{P_{n,t}^{1-\eta}} d_{ni,t}^{1-\eta}$. Following Anderson and Van Wincoop (2003), this system of equations is satisfied by[3]:

$$CMA_{i,t} = FMA_{i,t} = MA_{i,t} = \sum_{n \in N} \frac{d_{ni,t}^{1-\eta} X_{n,t}}{MA_{n,t}} \tag{6}$$

## D Income

Let $y_{n,t}$ be the nominal income per labor unit and $r_{n,t}$ the land rent at location $n$ at time $t$.[4] A worker who starts the period at $n$ will then receive real income:

$$Y_{n,t} = \frac{y_{n,t}}{P_{n,t}^{\alpha} r_{n,t}^{1-\alpha}} \tag{7}$$

Following Monte, Redding, and Rossi-Hansberg (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:

$$y_{n,t} L_{n,t} = w_{n,t} L_{n,t} \tag{8}$$

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

$$r_{n,t} = \frac{(1-\alpha) y_{n,t} L_{n,t}}{H_{n,t}} = \frac{(1-\alpha) w_{n,t} L_{n,t}}{H_{n,t}} \tag{9}$$

This implies that the expected lifetime utility of a representative worker in location $n$ at time $t$

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[3] As discussed in Anderson and Van Wincoop (2003) and Allen and Arkolakis (2022), the market access terms are equal up to scale and the general solution is $CMA_{i,t} = \lambda MA_{i,t}$ and $FMA_{i,t} = \frac{1}{\lambda} MA_{i,t}$ for any nonzero $\lambda$. The constant terms $\lambda$ cancel in and therefore do not affect estimation of the model.

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

can be expressed as:

$$(10)\; V_{n,t} = \alpha ln w_{n,t} - \alpha ln P_{n,t} - (1-\alpha) ln \left( \frac{(1-\alpha)L_{n,t}}{H_{n,t}} \right) + \nu ln \sum_{i \in N} \left( exp\left[ \beta V_{i,t+1} - \mu_{in} + B_{i,t} \right] \right)^{\frac{1}{\nu}}$$

## E 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 $\{FMA_{n,t}, CMA_{n,t}\}$ 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:

$$(11) \qquad w_{i,t} L_{i,t} = \frac{L_{i,t}^{\frac{1-\eta}{1-\sigma}} \left( \frac{w_{i,t}}{A_{i,t}} \right)^{1-\eta}}{(\sigma F)^{\frac{1-\eta}{1-\sigma}} \left( \frac{\sigma}{\sigma-1} \right)^{\eta-1}} FMA_{i,t}$$

2. Market access is given by:

$$(12) \qquad FMA_{i,t} = \sum_{n \in N} \frac{d_{ni,t}^{1-\eta} w_{n,t} L_{n,t}}{CMA_{n,t}}, \;\; CMA_{n,t} = \sum_{i \in N} \frac{d_{ni,t}^{1-\eta} w_{i,t} L_{i,t}}{FMA_{i,t}}$$

3. Expected lifetime utilities satisfy:

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

(13)

4. Migration shares satisfy:

$$(14) \qquad m_{in,t} = \frac{\left( exp\left[ \beta V_{i,t+1} - \mu_{in} + B_{i,t} \right] \right)^{\frac{1}{\nu}}}{\sum_{k \in N} \left( exp\left[ \beta V_{k,t+1} - \mu_{kn} + B_{k,t} \right] \right)^{\frac{1}{\nu}}}$$

5. The evolution of labor units is given by:

$$(15) \qquad L_{n,t+1} = \sum_{i \in N} m_{ni,t} L_{i,t}$$

Following Caliendo, Dvorkin, and Parro (2019), a stationary equilibrium of the model is a sequential equilibrium such that the endogenous variables are constant for all $t$.

### F Aggregate welfare

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

$$V_{n,t} = \sum_{s=t}^{\infty} \beta^{s-t} ln \left( \frac{w_{n,s}^{\alpha} exp\left(B_{n,s}\right)}{P_{n,s}^{\alpha} \left(\frac{(1-\alpha)L_{n,s}}{H_{n,s}}\right)^{1-\alpha} \left(m_{nn,s}\right)^{\nu}} \right) \tag{16}$$

Denoting by $\widehat{x}$ the value of a variable $x$ under an alternative scenario for the economy's fundamentals, this yields an expression for the consumption equivalent change in welfare from the change in the economy's fundamentals as in Caliendo, Dvorkin, and Parro (2019), as described in Appendix IV:

$$\triangle Welfare_{n,t} = (1-\beta) \sum_{s=t}^{\infty} \beta^{s-t} ln \left( \frac{\left(\frac{\widehat{w_{n,s}}}{w_{n,s}}\right)^{\alpha} \frac{exp\left(\widehat{B_{n,s}}\right)}{exp\left(B_{n,s}\right)}}{\left(\frac{\widehat{P_{n,s}}}{P_{n,s}}\right)^{\alpha} \left(\frac{\widehat{L_{n,s}}/L_{n,s}}{\widehat{H_{n,s}}/H_{n,s}}\right)^{1-\alpha} \left(\frac{\widehat{m_{nn,s}}}{m_{nn,s}}\right)^{\nu}} \right) \tag{17}$$

This measure is aggregated across locations in Vietnam ($n \in VN$) using a utilitarian approach which captures the mean value across all locations weighted by their respective initial population shares:

$$\triangle Welfare_{t} = \sum_{n \in VN} \frac{L_{n,t}}{\sum_{i \in VN} L_{i,t}} \left\{ (1-\beta) \sum_{s=t}^{\infty} \beta^{s-t} ln \left( \frac{\left(\frac{\widehat{w_{n,s}}}{w_{n,s}}\right)^{\alpha} \frac{exp\left(\widehat{B_{n,s}}\right)}{exp\left(B_{n,s}\right)}}{\left(\frac{\widehat{P_{n,s}}}{P_{n,s}}\right)^{\alpha} \left(\frac{\widehat{L_{n,s}}/L_{n,s}}{\widehat{H_{n,s}}/H_{n,s}}\right)^{1-\alpha} \left(\frac{\widehat{m_{nn,s}}}{m_{nn,s}}\right)^{\nu}} \right) \right\} \tag{18}$$

## II 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. To capture inter- as well as intra-national trade, an additional spatial unit is included to represent foreign markets.

### A Geographic data

I assign the location of each spatial unit in Vietnam 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 (2016)).

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 (Jarvis et al. (2008a)). 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 (ICEM (2009), GFDRR (2015)), 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, Below, and Hoyois (2015)).

## B Population data

The population of each spatial unit in 2010 and 2000 is calculated using the GPW dataset (CIESIN (2016)), which uses district-level data from Vietnam's Population Census. In order to evaluate how well the model predicts dynamic changes in the spatial distribution of the population, 2015 and 2019 data on province-level populations is obtained from the General Statistics Office of Vietnam (GSO (2020)).[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 (Forbes (1996), Falvey (2010)). 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, Balk, and Anderson (2007)). While historically important, the LECZ has been on a trajectory of relative 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 decline in the sub-5m LECZ's population share.[8]

## C Economic data

The central measure of district-level economic activity in 2010 is expenditure per capita data from Lanjouw, Marra, and Nguyen Viet (2013b). This dataset uses small area estimation techniques combining data from the Vietnam Household Living Standards Survey (VHLSS, described at Appendix II) 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, Gragnolati, and Zaman (2002)). In robustness specifications, I instead use district-level wage data from the Vietnam Enterprise Census (VEC, described at Appendix II). Consistent with the evidence of an inland shift in the locus of

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[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] Districts with more than 90% of their land area in the sub-5m LECZ experienced a decline in their population share from 36% in 2000 to 34% in 2010.

economic activity from population trends described in Section B, the sub-5m LECZ also experienced slower wage growth from 2000 to 2010.[9]

## D 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.[10] 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.

## E 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 II.[11] 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[12], 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 mapped 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 II 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

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[9] For instance, districts with more than 90% of their land area in the sub-5m LECZ experienced a population-weighted average increase in expenditure per capita of 181% versus a country average of 190%.

[10] International migrants are excluded from the analysis, consistent with the model's assumption of immobility of labor between countries (see Section I). 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.

[11] 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 quality and utilization of Vietnam's railway network is low (e.g. Nogales (2004), ADB (2012)). To calculate bilateral transport costs within Vietnam, I therefore consider only road, inland waterway and coastal shipping routes.

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

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 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 II.

## F International trade

The trade cost from each spatial unit centroid in Vietnam to international markets is calculated as the product of the iceberg trade cost from the centroid to the nearest international port and the estimated ad valorem equivalent international trade cost for lower middle income countries in 2010 from Arvis et al. (2016).[13] Data on the population in foreign markets is obtained from UNDESA (2019), and on GDP and land area from World Bank (2010).

## G Road construction costs

I calculate the relative construction costs of realized and counterfactual road upgrades following the methods used in Faber (2014) and Alder (2023). These use a construction cost function based on the engineering literature, which gives relative road construction costs for area cells on different terrains:

$$\textit{Construction Cost} = 1 + \textit{Slope} + (25 \times \textit{Builtup}) + (25 \times Water) + (25 \times Wetland) \tag{19}$$

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 (19) 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 II 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.

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[13] International ports comprise 26 international seaports (described at Appendix II), fourteen international border road connections of the Asian Highway Network and Greater Mekong Subregion cross-border road network (geo-referenced from ERIA (2010) and ADB (2010)) and Vietnam’s three major international airports (obtained from https://www.naturalearthdata.com/).

# III Model Parameterization and Calibration

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

## A Parameterizing iceberg trade costs

The methods described in Section II yield bilateral transport costs between each pair of Vietnam's spatial units, within each spatial unit, and between each spatial unit and international ports. I use these to parameterize iceberg trade costs by combining 2009 data on inter-provincial trade flows from JICA (2010a) and 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 $e_{ni}$.[14] Taking logarithms of the gravity Equation (5) for pairs with positive trade in a given time period yields:

$$ln(X_{ni}) = \chi_i + \psi_n + \phi(1-\eta) ln(t_{ni}) + \varepsilon_{ni} \tag{20}$$

where the origin location fixed effect $\chi_i$ controls for population $L_i$, wages $w_i$ and productivities $A_i$, while the destination location fixed effect $\psi_n$ controls for aggregate expenditure in $n$ and the multilateral resistance term in the denominator of Equation (5).

I estimate this equation for all province pairs with positive trade flows in 2009. Given the potential endogeneity of transport costs, I instrument measured log transport costs between province pairs using the log geodesic distance between province centroids. This yields a coefficient on $ln(t_{ni})$ of $\phi(1-\eta) = -1.84$.[15] To obtain the elasticity of iceberg trade costs with respect to measured transport costs $\phi$ from this estimate, a value is also needed for the CES parameter $\eta$. I calibrate this parameter using the method outlined in Kucheryavyy, Lyn, and Rodríguez-Clare (2023), which derives expressions for trade and scale elasticities in the generalized Krugman model as a function of the elasticities of substitution across location bundles and across varieties within a location bundle, together with data from Vietnam. 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 $\eta - 1 = 6.92$. Combining this estimate with the gravity estimate of $\phi(1-\eta) = -1.84$ yields a value for the elasticity of iceberg trade costs with respect to measured transport costs of $\phi = 0.27$.

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[14] Other studies in the literature use a similar approach relating trade flows to distance (e.g. Redding (2016), Monte, Redding, and Rossi-Hansberg (2018)), which will not be appropriate here given the focus on changes in transport infrastructure. As discussed in Monte, Redding, and Rossi-Hansberg (2018), the model implies prohibitive trade costs, $d_{ni} \to \infty$, for province pairs for which trade flows are zero, which may be interpreted as, for instance, trade requiring unmodeled prior investments in transport infrastructure.

[15] As a check on the functional form specification, regressing the logarithm of inter-provincial trade flows and fitted values of the first stage 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. A similar coefficient of -1.82 is obtained where measured transport costs are not instrumented using distance; results are robust to instead parameterizing $\phi$ based on this estimate.

The CES parameter $\sigma$ is similarly obtained using the method outlined in Kucheryavyy, Lyn, and Rodríguez-Clare (2023). 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 $\sigma = 10.55$.[16]

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

## C 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[17]). 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).

## D Discount factor

The discount factor $\beta$ corresponds to a five-yearly discount factor, since the model is simulated at five-yearly intervals. Recent values of the annual discount rate used in the literature are centered on 2% when considering long-term investments such as infrastructure and climate change (e.g. Giglio, Maggiori, and Stroebel (2015), Drupp et al. (2018), Bauer and Rudebusch (2021), Rudik et al. (2022), Bilal and Rossi-Hansberg (2023)). I use this value (which implies a five-yearly discount factor of 0.91) in the central estimates, and examine the implications of alternative choices for the discount rate in Section V.

## E Calibrating district-level market access and productivities

The model can be used together with the data described in Section II and the parameters from the previous subsections to obtain the relative market access and productivity values across Vietnam's

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[16] Table 2 shows the robustness of results assuming alternative values for $\eta$ and $\sigma$ from other estimates in the literature described in Section V.

[17] 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.

districts that are consistent with the observed data being an equilibrium outcome of the model in an initial period. Inverting equilibrium conditions (11) and (12) 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 Vietnam Enterprise Census to estimate the average total factor productivity (TFP) of formal sector firms in each district. While the calibrated relative productivity levels are based on population and economic activity variables that are broader than the formal sector, this provides a test of how far the calibrated values are correlated with related measures of productivity derived from data not used in the estimation. 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 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 of log TFP derived from this are strongly positively correlated with the calibrated log productivity values by spatial unit, as shown in Table 1.

An additional out-of-sample test of the model's predictions can be conducted by using the structure of the model to estimate Vietnam's exports as a share of GDP.[18] The central calibration implies a ratio of Vietnam's exports to GDP of 70%, very close to out-of-sample estimates that exports represented 72% of Vietnam's GDP in 2010 (GSO (2015a)).

# IV Model Simulation and the Effects of Realized Road Upgrades

The motivating evidence from Section II 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.[19] In this Section, I describe how the data described in Section II is used to simulate forward the model in Section I to quantify the returns to the realized road investments made in Vietnam from 2000 to 2010, with and without accounting for the projected effects of sea level rise. In Section V, I then turn to counterfactual simulations of the model which consider how far the returns conferred by alternative transport infrastructure

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[18] Continuing with the notation above but now indexing domestic regions by $i, k, n$ and the rest of the world by $ROW$, total international exports $E$ can be calculated as the value of all trade flows from domestic locations to the rest of the world in time period $t$, where $d_{ROWn,t}$ is the iceberg trade cost from domestic region $n$ to foreign markets:

$$E_t = \frac{X_{ROW,t}}{P_{ROW,t}^{1-\eta}} \sum_{n \in VN} \frac{w_{n,t} L_{n,t}}{FMA_{n,t}} d_{ROWn,t}^{1-\eta} \tag{21}$$

[19] 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)).

investments are influenced by projected changes in the environmental vulnerability of coastal regions.

## A Simulating the baseline economy

The model is simulated forward at five year intervals to solve for the sequential equilibrium path of the endogenous variables in each location. This takes as given data on initial populations $L_{n,2010}$, wages $w_{n,2010}$ and five year migration rates $m_{in,2005-2010}$; and an assumed time path of land areas $H_{n,t}$, relative productivities $A_{n,t}$ and transport costs between district pairs ($d_{ni,t}$) and between each district and foreign markets ($d_{ROWn,t}$). In the central scenario incorporating a gradual increase in the sea level, the future paths of land areas, productivities and transport costs are influenced by inundation as described in Section B. A separate simulation of the baseline economy is also conducted abstracting from future sea level rise, in which these variables are held constant. The baseline analysis assumes that amenities $B_n$ and migration costs $\mu_{ni}$ remain constant over time.

Following Caliendo, Dvorkin, and Parro (2019), an iterative solution algorithm is used which solves equilibrium conditions (11), (12) and (15) together with the remaining equilibrium conditions in relative time differences (A14) and (A15) (derived at Appendix IV). 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 V.

In addition to the out-of-sample evaluation results for productivities and the share of exports in GDP, an evaluation of the dynamic predictions of the model 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 (GSO (2020)). 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 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 0.32 and 0.63 respectively.[20]

## B Modeling future sea level rise

There is considerable variation in projections of global sea level rise and its impacts. While more extreme estimates project rises up to 5 meters over the next century (Dasgupta et al. (2009)), central estimates lie in the range of 0.2-0.3 meters by 2050 and 0.4-0.8 meters by 2100 (Oppenheimer et al. (2019)). Estimates in Vietnam project sea level rises of 0.23-0.27 meters by 2050 and 0.44-0.73 meters by 2100 (Thuc et al. (2016), Ngo-Duc et al. (2021)), with land subsidence in low lying

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[20] This comparison is conducted for the central case with sea level rise realized gradually over the next 100 years, which influences land areas $H_{n,t}$, productivities $A_{n,t}$ and transport costs $d_{ni,t}$ and $d_{ROWn,t}$ over time as described in Section B, holding constant all other parameters of the model. A slightly weaker fit is obtained for the simulated results with no inundation: observations remain close to the 45° line, with an $R^2$ of 0.20 and 0.54 respectively.

regions threatening more severe inundation exceeding 1 meter (Erban, Gorelick, and Zebker (2014), Minderhoud et al. (2019)). I use a central scenario of a gradual rise reaching 1 meter by 2110.

In simulations of the model incorporating future sea level rise in Vietnam, this is manifested in three ways. First, inundated areas will see a gradual decline in their available land area $H_{n,t}$. Second, productivities in low elevation coastal areas decline as they become inundated. Third, inundated roads become more costly to traverse, increasing trade costs $d_{ni,t}$ and $d_{ROWn,t}$. In the baseline estimates, I assume that agents are perfectly foresighted about these changes, and in Section V consider robustness to instead assuming myopic agents for whom sea level rise arrives as an unanticipated shock.

To model inundation of land, I calculate the proportion of each district's land area below 1 meter[21] and reduce its available land area by this amount in equal increments each period from 2010 to 2110.[22] Sea level rise is also projected to have detrimental productivity impacts in coastal areas, for instance as a result of declines in aquaculture and agricultural productivity induced by saltwater intrusion, damages from more intense tropical cyclones or reduced attractiveness of coastal regions for tourism (IPCC (2001)). I assume percentage productivity declines by 2110 equal to the share of each district's land area below 1 meter, which yields aggregate productivity reductions consistent with other estimates of such effects in this and similar contexts over the next century.[23] The total decline over this period is interpolated across the five-year intervals used in the estimation.

I base assumptions about the per-kilometer cost of traversing inundated roads on recent models of the disruptive impact of inundation on road transportation (Pregnolato et al. (2017)), which predict acute declines in road speeds as water depths approach 0.25 meters and recognize 0.30 meters as the ultimate threshold for safe road transportation. Given these sharp declines at inundation depths below one meter that are projected to be reached by mid-century, I assign road stretches intersecting the zone at or below zero meters elevation to gradually face inundated travel costs by 2050.[24] To avoid corner solutions where impassable roads result in certain areas being cut off entirely, I assume that travel speeds on inundated roads decline to 3 kilometers per hour from 2030 (Pregnolato et al. (2017)'s estimated travel speed when water reaches the undertray of the car) and to a minimum of 1 kilometer per hour from 2050, with a commensurate increase in the average direct cost of transport

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[21] Elevation data for each 3 arc-second pixel is reported in integer values.

[22] 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.

[23] Across districts with at least 1% of their land area below 1 meter elevation, the median productivity decline is 13% by 2110. This is comparable to estimates of the impact of sea level rise via salinity intrusion on aquaculture in the Mekong Delta (Trieu and Phong (2015)) and rice production in the Ebro Delta (Genua-Olmedo et al. (2016)).

[24] I assign road edges with at least 10% of their length below zero meters to face inundated travel costs in order to avoid assigning inundated travel costs to road edges that may intersect inundation polygons as a result of minor mapping inaccuracies. As shown in Section V, qualitatively similar results are obtained when this threshold is increased such that only 1% of the length of the road network faces inundated travel costs, approximately the length projected to be directly submerged by 2050 (based on estimates in ADB (2013) that a 1 meter rise in the sea level would permanently submerge 4% of Vietnam's road network, and projected sea level rise of 0.25 meters by 2050). The latter is likely to substantially underestimate the share of roads on which travel speeds are affected by inundation given that congestion typically extends along an inundated road edge beyond the directly submerged portion.

per ton-km (one off mobilization costs are assumed to be unchanged).[25] For the intervening periods, travel costs on these road edges are assumed to increase in equal increments.

## C 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 $d_{ROWi}$ that reflect the transport network that would have existed had there been no road upgrades made from 2000 to 2010.[26] To isolate the effect of road upgrades 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. The change in welfare induced by this change in the economy's fundamentals is given by Equation (18).

In the central scenario with a gradual 1 meter rise in the sea level over 100 years, Equation (18) reveals that aggregate welfare is 1.13% 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. Incorporating the effects of future sea level rise in the simulations has important implications for the projected gains from the road investments: assuming that there is no future sea level rise in Equation (18) yields much higher estimated welfare gains from the realized road investments of 1.73%.[27] The fact that accounting for future sea level rise reduces estimated welfare gains by 0.6 percentage points, or 35%, reflects the fact that a large share of upgraded roads are gradually lost to inundation, or connect inundated areas. Figure 6 shows the dynamic trajectories of estimated gains as the time horizon over which welfare gains are aggregated increases. This demonstrates increasingly pronounced divergence of the estimated gains with and without accounting for future inundation, with welfare gains coverging towards 1.13% and 1.73% respectively as the time horizon over which welfare gains are aggregated increases.

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 countries (e.g. Allen and Arkolakis (2014), Baum-Snow et al. (2018), Alder (2023)), the results of this analysis suggest that

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[25] Results are robust to assuming that the minimum travel speed is held constant at 3 kilometers per hour from 2030 and does not decline further, as shown in Table 2. Table 2 also shows the robustness of results to assuming a minimum inundated travel speed of double this value.

[26] Information on counterfactual road investments is assumed to arrive as an unexpected shock in 2010, as in Caliendo et al. (2019). As the observed migration flows from 2005 to 2010 reflect the realized road network in 2010 under the model's assumption of perfect foresight, I follow Caliendo et al. (2019) and use agents' actions before the shock to solve for the sequential equilibrium under the counterfactual fundamentals. This is based on a distribution of economic activity in 2005 that reflects migration shares from 2005 to 2010 and the 2000 road allocation, holding other fundamentals constant; results are robust to also assuming that inundation alters relative productivities and land areas from 2005 to 2010 in line with their future trajectories.

[27] The estimated welfare gains from the realized road investments are of a comparable magnitude to those estimated to have resulted from major road investment projects in other settings. For instance, Allen and Arkolakis (2014) estimate that removing the US Interstate Highway System would result in (static) welfare losses of 1.1-1.4%, while Alder (2023) estimates that aggregate real GDP in India would have been 0.8% lower in 2012 (net of construction and maintenance costs) if the Golden Quadrilateral highway had not been built.

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 (Fajgelbaum and Schaal (2020), Allen and Arkolakis (2022)), where considering the dynamic implications of future climate change may have important implications for designing infrastructure improvements. I turn to this in the next section.

## V Sea Level Rise 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 at-risk areas. In order to investigate this, I simulate the impacts of counterfactual road investment allocation rules of the same total investment amount as the status quo road investments that were made between 2000 and 2010, but which anticipate future sea level rise to varying degrees.

### A Counterfactual allocations

I focus attention on two sets of counterfactual allocation rules for road investments made between 2000 and 2010: the first based on a rule-of-thumb allocation closely linked to those used by transport planners in practice, and the second an allocation rule that more closely approximates the efficient solution implied by the model's optimality conditions. In both cases, I consider a version of the allocation rule that ignores the effects of future sea level rise, and an otherwise comparable implementation of the same rule but which reflects future inundation risks. All counterfactuals considered have the same total cost as the status quo road investments, as determined by the road construction cost equation (19).

The first set of counterfactuals considered use a simple allocation rule linked to those used by transport planners in practice (Xie and Levinson (2011), Burgess et al. (2015)). This rule prioritizes bilateral upgrades between spatial unit pairs according to their pairwise market potential (see, for example, Overman, Redding, and Venables (2003)) in 2000, defined as:

$$\frac{L_k}{\sum_{i \in VN} L_i} \frac{w_j L_j}{\boldsymbol{dist_{jk}}} + \frac{L_j}{\sum_{i \in VN} L_i} \frac{w_k L_k}{\boldsymbol{dist_{jk}}} \tag{22}$$

where the first term captures gains in location $k$ from improving access to location $j$ with GDP $w_j L_j$, inversely weighted by the straight-line distance $dist_{jk}$ between the two markets, and weighted by location $k$'s own population size to imply a utilitarian approach to aggregating gains across populations. The second term captures a symmetrical effect for location $j$ when its connection to location $k$ is improved. For connections between Vietnam's districts and international markets, the district population weighted measure divides GDP in the rest of the world by the distance to foreign markets $dist_{ROWk}$, measured as the bilateral distance from the district centroid to the nearest international port plus a fixed term equal to the great circle distance between the capital of Vietnam and those of its top ten international trading partners in 2000 weighted by their contemporary export shares:

$$\frac{L_k}{\sum_{i \in VN} L_i} \frac{w_{ROW} L_{ROW}}{\boldsymbol{dist_{ROWk}}} \tag{23}$$

I assume that planners use data on populations, wages and bilateral distances from the year 2000, the beginning of the 2000 to 2010 investment period. As such, this allocation rule draws on data which would have been available in the period in which the allocation decision was made, and prioritizes bilateral connections for upgrades based on a simple rule-of-thumb building on those actually used by policymakers.

The central contribution of the counterfactual analysis in this section is to examine the importance of dynamic environmental considerations in designing infrastructure improvements. I therefore evaluate two counterfactuals based on this allocation rule that are differentially foresighted about the future effects of sea level rise. The first aims to maximize pairwise market potential ignoring the implications of future sea level rise. To construct this counterfactual, I rank pairwise connections according to their pairwise market potential in 2000; use the Network Analyst tool in ArcGIS to find the connection between each of these pairs with the lowest travel cost[28]; and allocate one category road upgrades to these bilateral connections until the same total investment as under the status quo road investments has been allocated. The second counterfactual uses the same ranking of pairwise connections by 2000 market potential, but anticipates the impact of future sea level rise on road transportation costs by instead upgrading the route between selected pairs that would have the lowest travel cost once inundation of the road network takes effect as described in Section IV, reducing travel speeds on inundated stretches to 3 kilometers per hour. Upgrades are again allocated in this order until the same total budget as allocated under the status quo road investments is reached.

The preceding simulations aim to shed light on how far consideration of future inundation should influence the allocation of infrastructure investments according to rules-of-thumb used by policymakers based on available data. While this may be the most policy-relevant allocation rule in practice, a recent literature highlights that more efficient allocation decisions can improve on these simple rules-of-thumb. This raises a question as to whether consideration of future environmental change may also influence other potential allocation rules that more closely approximate an efficient allocation. To investigate this, I consider a second set of counterfactuals that more closely approximate efficient network upgrades in a computationally feasible manner.

Appendix VI considers a simplified optimal infrastructure allocation problem whereby the Government of Vietnam allocates a fixed road improvement budget to maximize the population-weighted average expected lifetime utility in Vietnam.[29] The resultant allocation rule derived from this max-

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[28] In the case of spatial unit - international market pairs, this is represented by the lowest cost route from the spatial unit to the nearest international port in this and subsequent counterfactuals.

[29] This optimization problem relates to a recent literature identifying optimal networks in particular classes of static general equilibrium spatial models (e.g. Fajgelbaum and Schaal (2020)). 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 and in a dynamic setting, the model I use is not amenable to such approaches to identifying globally optimal network

imizes the welfare contribution of road investments via endogenous improvements in market access. As shown in Appendix VI, this can be approximated by prioritizing road upgrades along pairwise connections between Vietnam's districts $j$ and $k$ according to:

$$\sum_{t=0}^{\infty} \beta^t \left\{ d_{jk,t}^{-\eta} \left[ \frac{L_{k,0}}{\sum_{i \in VN} L_{i,0}} \frac{1}{MA_{k,t}} \frac{w_{j,t} L_{j,t}}{\boldsymbol{MA_{j,t}}} + \frac{L_{j,0}}{\sum_{i \in VN} L_{i,0}} \frac{1}{MA_{j,t}} \frac{w_{k,t} L_{k,t}}{\boldsymbol{MA_{k,t}}} \right] \right\} \tag{24}$$

and between a district $j$ and the nearest international port according to:

$$\sum_{t=0}^{\infty} \beta^t \left\{ d_{jROW,t}^{-\eta} \left[ \frac{L_{j,0}}{\sum_{i \in VN} L_{i,0}} \frac{1}{MA_{j,t}} \frac{w_{ROW,t} L_{ROW,t}}{\boldsymbol{MA_{ROW,t}}} \right] \right\} \tag{25}$$

These expressions bear a close resemblance to a dynamic pairwise counterpart of static market access, commonly used in economic geography frameworks to capture the importance of trade cost-weighted economic activity (Overman, Redding, and Venables (2003), Redding and Rossi-Hansberg (2017)), which is intuitively an important determinant of the returns to infrastructure investments (Santamaria (2023)). In Equations (24) and (25), the standard market access formulation is adjusted to account for diminishing marginal utility, weighted by initial population given the utilitarian formulation for welfare, and calculated as the present discounted value over future periods, drawing on the projected dynamic path of wages, populations, transport costs and market access across locations over time. This allocation rule provides a model-consistent approximation of the optimal allocation. While this likely does not achieve the fully optimal dynamic allocation of road investments (as discussed at Appendix VI), it is the closest approximation that remains computationally tractable in this dynamic estimation.

I again evaluate two counterfactuals based on this allocation rule, one which ignores the implications of future sea level rise and one which accounts for future inundation. In both cases, the time path of the component variables $L_{i,t}$, $w_{i,t}$, $MA_{i,t}$ and $d_{ij,t}$ are obtained from the simulated time path of the economy had no road upgrades been made between 2000 and 2010. The first counterfactual ranks pairwise connections according to the allocation rule above, where the time path of these component variables is simulated in the scenario with no future sea level rise. The Network Analyst tool in ArcGIS is used to find the connection between each of these pairs with the lowest travel cost, and one category road upgrades are then allocated to these bilateral connections in order of the dynamic pairwise market access ranking, until the same total investment in road upgrades as under the status quo road investments has been allocated. I compare this with a counterfactual that maximizes the same measure of dynamic pairwise market access, but anticipates future sea level rise by both instead drawing on the time path of the component variables $L_{i,t}$, $w_{i,t}$, $MA_{i,t}$ and $d_{ij,t}$ in the scenario *with* future sea level rise, and upgrading the route between selected pairs that would have the lowest travel cost once inundation takes effect, until the same total budget has been reached.

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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 (2023)) 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.

The implied road networks under each of these counterfactuals are shown in Figure 7. As is evident from the figure, all counterfactuals imply some concentration of upgrades in the LECZ – in line with its concentration of existing economic activity, on which the market potential and market access measures are based – but are less strongly concentrated in the LECZ than the status quo road investments. The implied road networks under the counterfactuals which are foresighted about future inundation are shown in the right-hand panels of Figure 7. Intuitively, these maps demonstrate a lower degree of coastal concentration than the allocations in the left-hand panels of the figure, which are unconstrained by imperatives to avoid vulnerable low-lying areas. The share of upgraded road length at less than 1 meter elevation is 6% and 7% for the unconstrained pairwise market-potential and dynamic market-access maximizing counterfactuals respectively, and 5% and 4% for their corresponding counterparts which take into account future inundation. All of these shares are below the 11% share of road upgrade length that lies below 1m elevation for the status quo road investments.

## B 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 under both counterfactual allocation rules. Figure 8 shows welfare gains achieved by each counterfactual relative to the status quo road investments. Results are shown in the central scenario with a gradual 1 meter rise in the sea level over 100 years (left hand panel) and when abstracting from future inundation (right hand panel). The estimates suggest that significant gains would have been available from alternative allocations of the road investments made from 2000-2010. This finding is robust both with and without accounting for the impacts of future inundation, and is consistent with an existing literature demonstrating that realized road upgrades are not made optimally in other contexts (Graff (2019), Fajgelbaum and Schaal (2020)).[30] Given that each of the counterfactuals is significantly less coastally concentrated than the status quo road investments, as described in Section A, the results suggest that the realized upgrades may have over-invested in coastal areas.[31]

In the central scenario accounting for future sea level rise (left hand panel), the foresighted counterfactual allocations avoiding the most vulnerable regions (in blue) achieve higher gains than

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[30] The magnitude of potential gains from welfare-enhancing reallocation of road investments is also in line with those estimated in other settings. For example, Fajgelbaum and Schaal (2020) estimate that the welfare gain from optimal reallocation of existing road networks in 24 European countries ranges from 0.1% to 7%, with an average of 2%, and Alder (2023) estimates that a budget-neutral reallocation of road investments in India could have achieved aggregate net income gains of 3.8% relative to the -0.8% aggregate net income effect of removing the actual investments.

[31] The literature has examined several reasons that infrastructure investments may not be allocated optimally (see, for instance, Glaeser (2010), Burgess et al. (2015), Do, Nguyen, and Tran (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 C).

their counterparts that do not take into account future inundation risks (in orange). The market potential maximizing allocation avoiding the most vulnerable routes achieves a welfare improvement relative to the status quo road investments of 1.30%, compared to the 1.26% gain achieved by the counterfactual that does not account for future inundation. The counterfactuals that aim to more closely approximate an efficient network intuitively achieve higher welfare gains than these simple rules of thumb, and demonstrate the same pattern: the welfare gains from the foresighted allocation (1.47%) exceed those from the allocation ignoring future inundation (1.39%). As discussed in more detail in Section C below, this reflects a dynamic tradeoff between the long-term gains from foresighted allocations reducing future vulnerability to sea level rise, and the short-term costs of sacrificing investments in densely populated coastal regions.

Failing to account for future sea level rise (right hand panel) 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. In this case, the allocations ignoring future inundation intuitively yield the highest gains, since the constraint to avoid low elevation regions is irrelevant in the absence of sea level rise. The market potential maximizing allocation that ignores future sea level rise sees estimated gains relative to the status quo road investments of 1.03%, compared to the 0.93% achieved by the foresighted market potential maximizing allocation. The estimated gains from the counterfactuals more closely approximating the efficient network yield the same qualitiative pattern, implying welfare gains of 1.24% and 0.83% respectively.

Accounting for future sea level rise in the left hand panel of Figure 8 renders all counterfactuals more valuable relative to the status quo than when future inundation is overlooked. This reflects the fact that the counterfactual allocations are less concentrated than the status quo road investments in areas that will be inundated in the future. The quantitative differences in implied welfare gains between the road allocation rules are constrained by the strong concentration of existing economic activity in coastal regions. This drives a reasonable coastal concentration of road upgrades under all counterfactual allocations, limiting the welfare gains available from adjusting investment strategies inland in the face of projected sea level rise. Nonetheless, the differences are sizable when compared to the magnitude of estimated gains from optimal reallocation of road investments in other settings. For instance, the percentage point differences in welfare gains achieved under the foresighted counterfactuals versus their counterparts ignoring future inundation are a substantial share of the welfare gains Fajgelbaum and Schaal (2020) estimate would obtain from optimally reallocating the entire transport network in some European countries. Even small percentage point differences translate into large monetary gains, underscoring that significant sums will be left on the table by failing to account for future inundation when making allocation decisions. Given the enormous investments being made in transportation infrastructure, these results highlight that consideration of future environmental change is central to assessing the returns to these investments and ensuring that their allocation is as efficient as possible.

## C Dynamic considerations

The results in the previous subsection rest on a dynamic tradeoff between the short-term costs of forgoing market access improvements in densely populated coastal areas versus the longer term gains from reducing exposure to inundation. Allocations that are not constrained to avoid vulnerable regions include 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, as the time horizon over which welfare gains are aggregated increases. Considering first the counterfactuals based on maximizing pairwise market potential (solid lines), in the first period of the simulation, the welfare gain from the counterfactual allocation ignoring future inundation relative to the status quo road investments exceeds that from the foresighted counterfactual allocation. As the time horizon over which welfare gains are aggregated is extended, however, welfare gains increase more rapidly for the latter. Once the time horizon extends to 2040, aggregate welfare gains are greater for the foresighted counterfactual allocation. Similarly for the counterfactuals that aim to get closer to the efficient allocation by maximizing the welfare contribution of road investments via endogenous improvements in market access (dashed lines), the allocation ignoring future sea level rise dominates until the horizon extends to 2050, after which the foresighted allocation sees higher aggregate welfare gains.

These relative dynamic trajectories highlight that, while higher aggregate long-run welfare gains are available from foresighted allocations avoiding vulnerable regions, this comes at the expense of the short-run costs of forgoing 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. Table 2 presents results using varying annual discount rates. As the discount rate is reduced, the welfare gains from the foresighted allocations exceed those from the unconstrained allocations over shorter time horizons, and the magnitude of the difference in aggregate welfare gains between these counterfactuals becomes more pronounced. Conversely, increasing the discount rate reduces the relative gains from the foresighted allocation rules accounting for future sea level rise relative to their unconstrained counterparts. When the annual discount rate is increased to 6%, the aggregate welfare gain from the unconstrained allocation exceeds that from the foresighted allocation in the scenario with sea level rise for both allocation rules based on pairwise market potential and dynamic pairwise market access considered here, though the difference in welfare gains between the unconstrained and foresighted allocations is much attenuated relative to the scenario where the effects of sea level rise are excluded from the simulations.

## D Robustness tests

The results 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.

### 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. The projected future productivity declines as sea level rise takes effect are then applied to this path of district productivities. In this case, the central findings remain 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.[32] 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 a 50% coastal premium 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.

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

### Growth in international trade

Another factor which might be expected to undergo secular change over the simulation period is the importance of international trade. As discussed in Section III, the baseline model performs well in predicting the (non-targeted) exports as a share of Vietnam's GDP in 2010. I consider the robustness of the central results to reducing the cost of reaching foreign markets from international ports in future periods such that the future trajectory of Vietnam's exports as a share of GDP is close to the observed shares in 2015 and 2020 (predicted shares of 74% in 2015 and 82% in 2020, compared to observed shares of 73% and 84% respectively (GSO (2021))). The central results are qualitatively similar in this case, as shown in Table 2.

### 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. Robustness 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 allocations to yield approximately the same welfare gains as (in the case of the pairwise market-potential maximizing allocation) or outperform (in the case of the allocation maximizing dynamic market access) the otherwise comparable foresighted allocations avoiding the most vulnerable regions in the case with inundation.

### 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 30 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 III. Table 2 shows that similar results obtain in this case.

### Land used in production function

In the baseline model, land $H_{n,t}$ is assumed to be used in consumption. The theoretical framework in Section I can be extended to incorporate land used in production as well as residentially. While data is not available to separate the share of land used in production versus consumption in each district, I test the robustness of the results to the alternative assumption that land is only used in production. The amended equilibrium conditions used in this case are derived at Appendix V. The results in this case are shown in Table 2 and demonstrate that the central findings are robust.

### Formal sector wage data

As outlined in Section II, 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.

### Alternative parameter choices

As described in Section III, I test the robustness of the results to alternative choices for the model's key migration elasticity and CES parameters. These results, shown in Table 2, reveal similar findings when the migration elasticity $\frac{1}{\nu}$ is set to 2 or 4 rather than the baseline value of 3. The results in the table also reveal that the findings are robust to alternative parameterizations for the CES parameters $\eta$ and $\sigma$; in particular when assuming $\eta = 7.41$ and $\sigma = 9.28$ based on an unweighted average of trade and scale elasticities in Bartelme et al. (2018), or $\eta = 7.1$ and $\sigma = 16.6$ following Faber and Gaubert (2019)'s estimates for the manufacturing sector in Mexico.

### Timing of stationary equilibrium

As discussed in Section IV, 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. Similar results are obtained when the model is re-simulated assuming that the stationary equilibrium is instead reached in 200 or 400 years, as shown in Table 2.

## VI 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 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 significant. 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 because 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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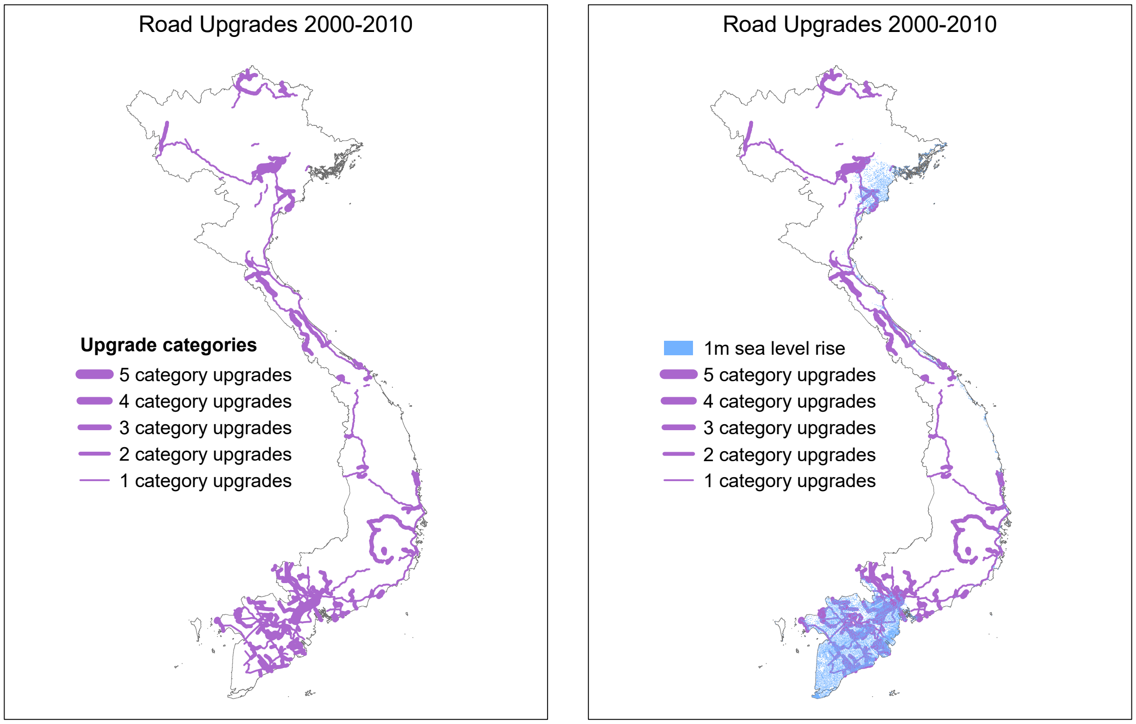
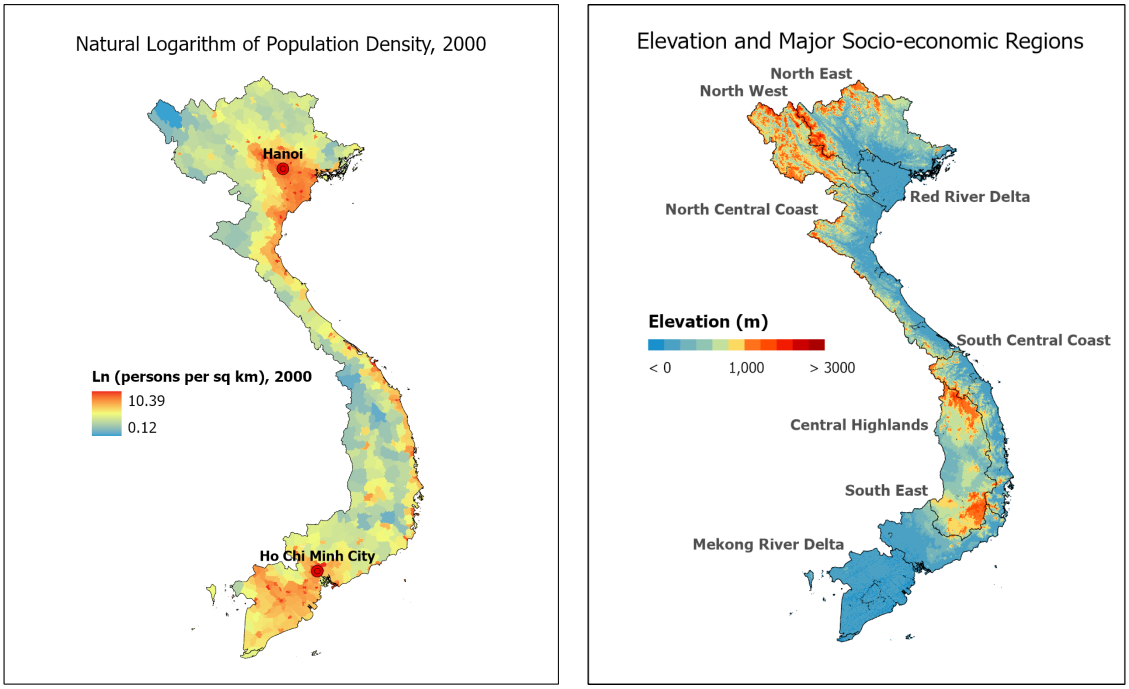
# Tables and Figures

Figure 1: Road investments in Vietnam, 2000-2010



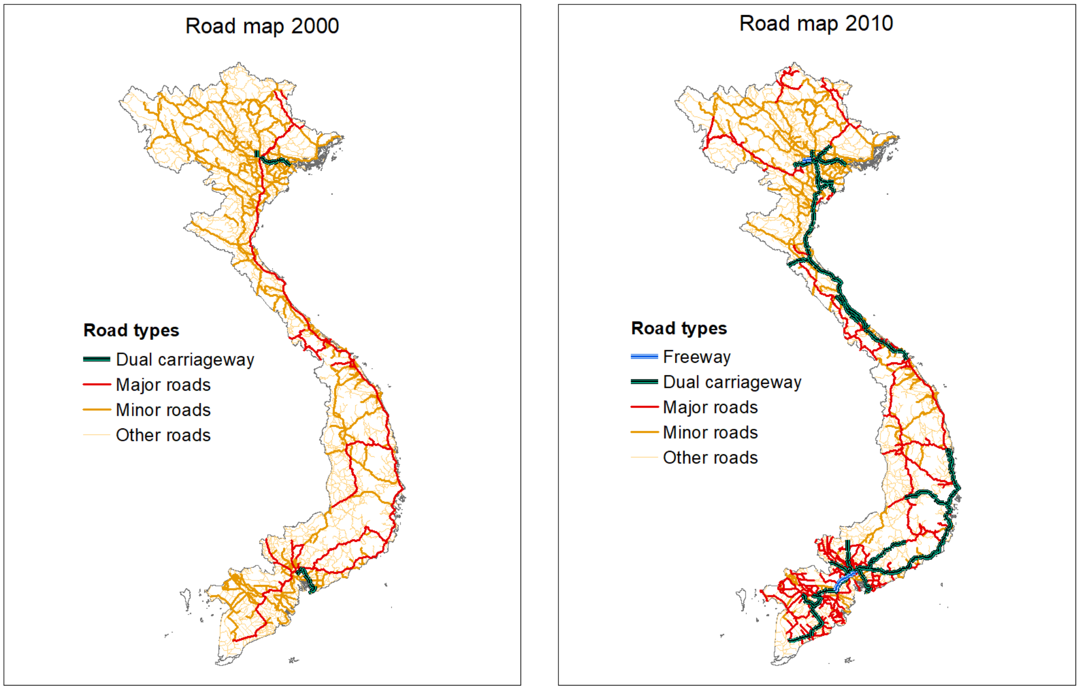
Note: Data sources and construction are described in Section II and Supplemental Appendix II.

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



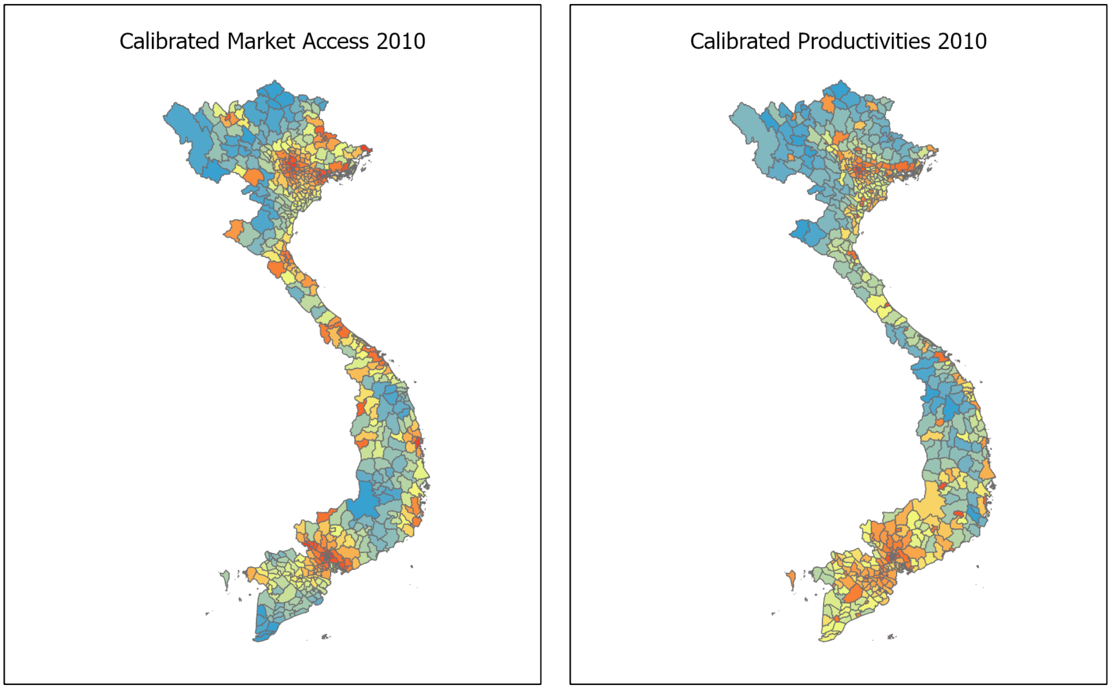
Note: Data sources and construction are described in Section II and Supplemental Appendix II.

Figure 3: Road maps of Vietnam, 2000 and 2010



Note: Data sources and construction are described in Section II and Supplemental Appendix II.

Figure 4: Calibrated market access and productivities in 2010



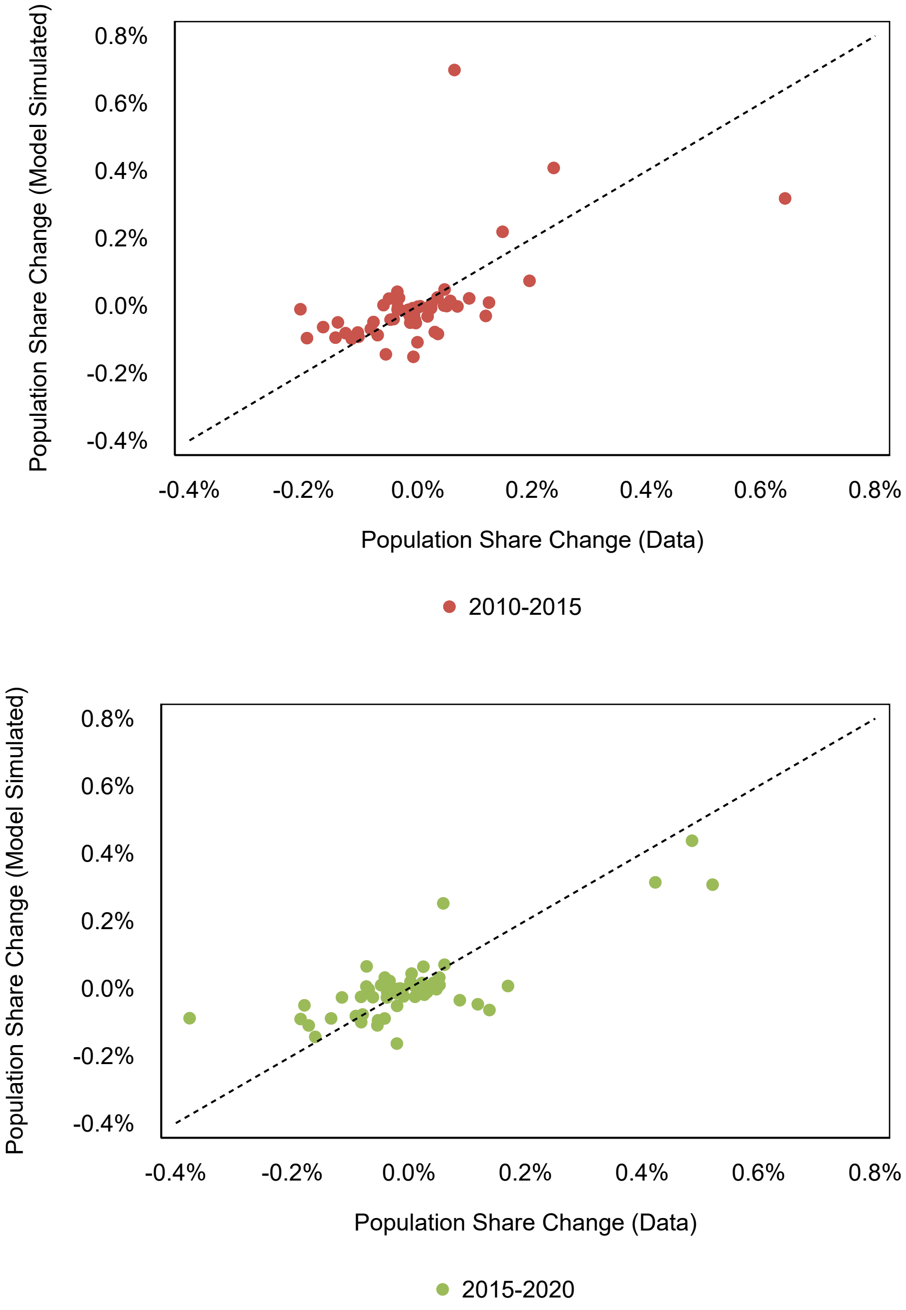
*Notes: Data are reported at the level of district-based spatial units. Red (blue) units indicate higher (lower) values.*

Table 1: Correlation between calibrated productivities and TFP in 2010

| Dependent variable: log calibrated relative productivity level by district | | |
|---|---|---|
| log TFP estimated using $Y = AK^{\frac{1}{3}}L^{\frac{2}{3}}$ | 0.280<br>(0.0244) | |
| log TFP estimated using $Y = AL$ | | 0.242<br>(0.0216) |
| Observations | 540 | 540 |
| R-squared | 0.196 | 0.190 |

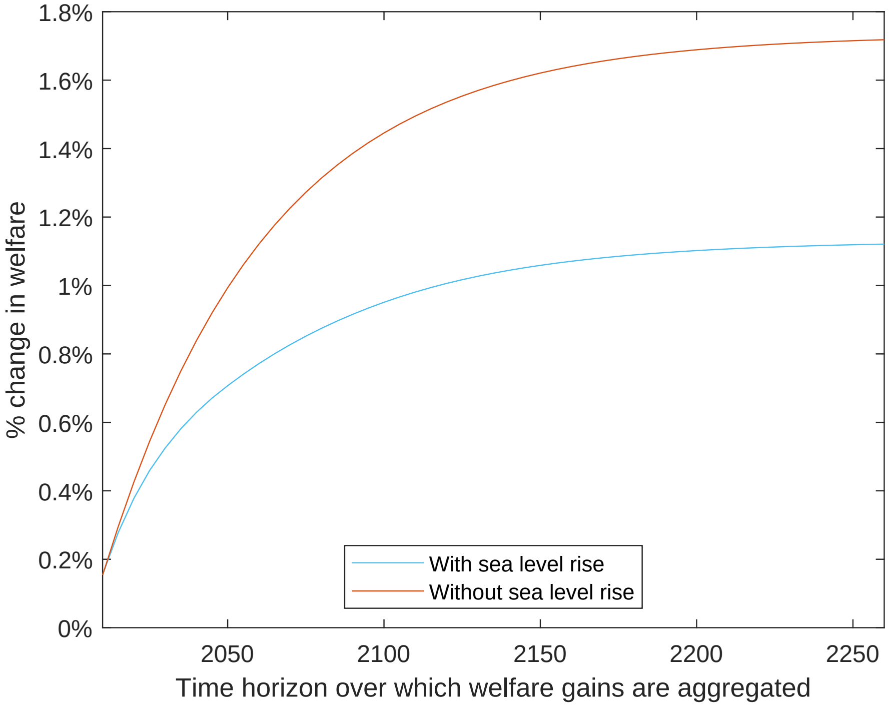
Standard errors in parentheses. Bivariate regression of log calibrated district-level productivity values on log district-level mean TFP of formal sector firms estimated as described in Section III.E.

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



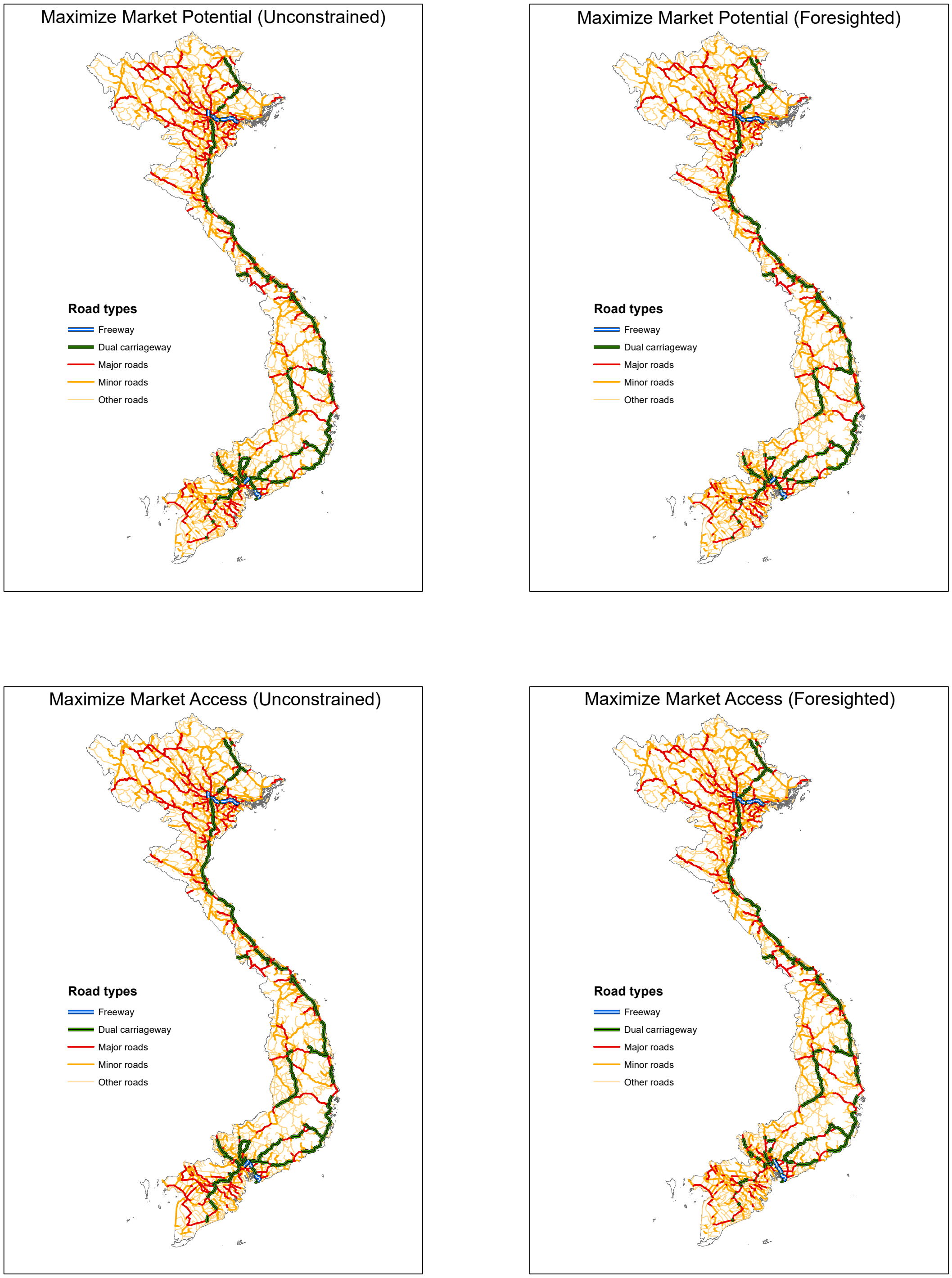
*Notes: Dashed lines denote 45° line. The linear trendline has equation* $y = 0.61x - 4 \times (10^{-8})$ *and* $R^2 = 0.32$ *for 2010-2015, and equation* $y = 0.59x - 5 \times (10^{-9})$ *and* $R^2 = 0.63$ *for 2015-2020.*

Figure 6: Dynamic aggregate welfare gains from realized road investments with and without sea level rise



*Notes: The figure compares aggregate welfare gains for the realized road upgrades with (blue line) and without (orange line) a 1 meter rise in the sea level realized gradually over 100 years, as the time horizon over which welfare gains are aggregated increases. The percentage change in welfare is measured in terms of consumption equivalent variation, relative to a scenario in which no roads had been upgraded.*

Figure 7: Counterfactual road networks


Maximize Market Potential (Unconstrained)

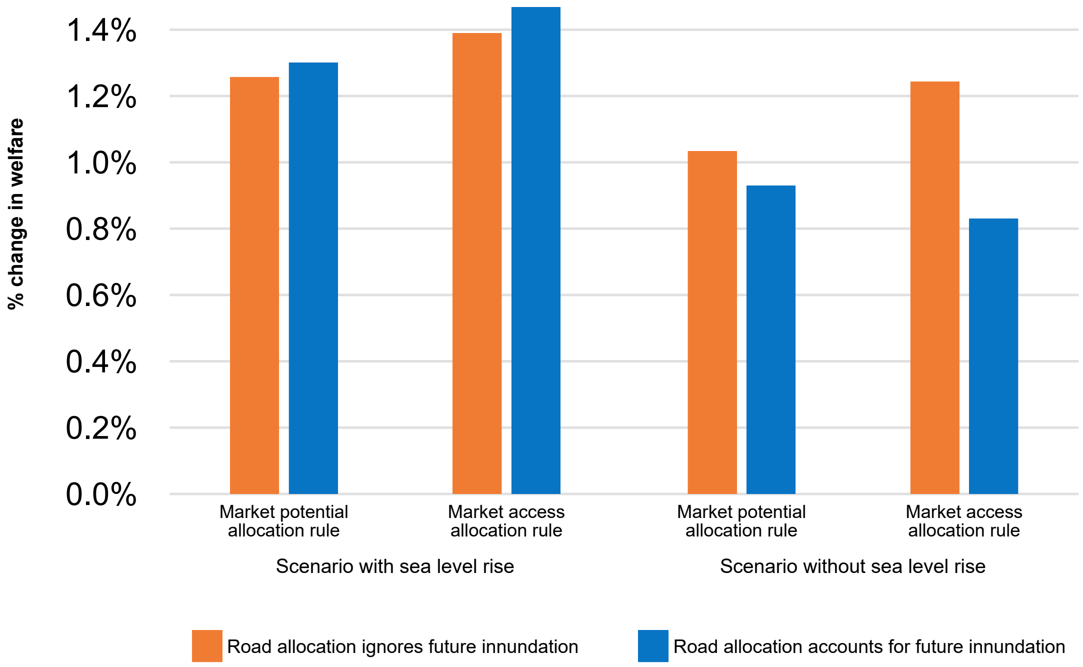
Maximize Market Potential (Foresighted)

Maximize Market Access (Unconstrained)

Maximize Market Access (Foresighted)

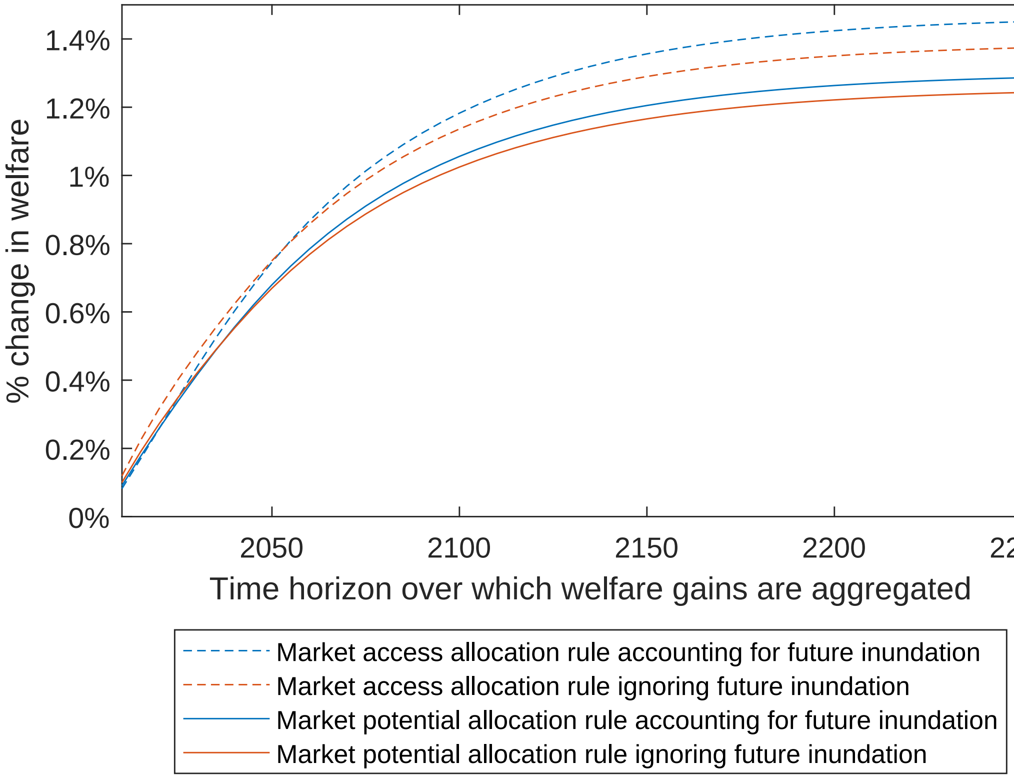
*Notes: 'Unconstrained' counterfactuals allocate road upgrades without accounting for future sea level rise. 'Foresighted' counterfactuals allocate road upgrades accounting for future sea level rise.*

Figure 8: Welfare gains from counterfactual road investments relative to status quo road investments



*Notes: The figure shows aggregate welfare gains versus the status quo road investments. The percentage change in welfare is measured in terms of consumption equivalent variation. Scenario with sea level rise incorporates a 1 meter rise in the sea level realized gradually over 100 years. Scenario without sea level rise assumes that sea levels will remain at current levels. Blue (orange) bars correspond to counterfactual road allocations that account for (ignore) future sea level rise.*

Figure 9: Dynamic aggregate welfare gains from counterfactual road investments relative to status quo road investments with sea level rise



*Notes: The figure compares aggregate welfare gains versus the status quo road investments for counterfactual allocations of road upgrades ignoring future inundation (orange lines) and counterfactual allocations accounting for future inundation (blue lines), as the time horizon over which welfare gains are aggregated increases. The percentage change in welfare is measured in terms of consumption equivalent variation. Market potential allocation rule (solid lines) refers to counterfactuals based on maximizing pairwise market potential. Market access allocation rule (dashed lines) refers to counterfactuals based on maximizing the welfare contribution of road investments via endogenous improvements in market access. All simulations incorporate a 1 meter rise in the sea level realized gradually over 100 years.*

## Table 2: Robustness tests

Welfare gains from counterfactual road investments relative to status quo road investments

| | Inundation scenario | | | | No inundation scenario | | | |
|---|---|---|---|---|---|---|---|---|
| | Maximize market potential ignoring future sea level rise | Maximize market potential accounting for future sea level rise | Maximize market access ignoring future sea level rise | Maximize market access accounting for future sea level rise | Maximize market potential ignoring future sea level rise | Maximize market potential accounting for future sea level rise | Maximize market access ignoring future sea level rise | Maximize market access accounting for future sea level rise |
| Central simulations | 1.26% | 1.30% | 1.39% | 1.47% | 1.03% | 0.93% | 1.24% | 0.83% |
| Annual discount rate 1% | 1.32% | 1.38% | 1.45% | 1.57% | 1.03% | 0.93% | 1.24% | 0.82% |
| Annual discount rate 6% | 1.12% | 1.11% | 1.26% | 1.18% | 1.04% | 0.94% | 1.24% | 0.84% |
| Inundated travel costs on 1% network | 1.329% | 1.334% | 1.469% | 1.475% | 1.03% | 1.02% | 1.24% | 1.16% |
| Minimum inundated travel speed 3km/hr | 1.12% | 1.16% | 1.26% | 1.32% | 1.03% | 0.93% | 1.24% | 0.83% |
| Minimum inundated travel speed 6km/hr | 1.01% | 1.03% | 1.15% | 1.20% | 1.03% | 1.04% | 1.24% | 0.89% |
| Productivities secular trends | 1.06% | 1.09% | 1.21% | 1.25% | 0.79% | 0.70% | 1.06% | 0.64% |
| Changing coastal amenities | 1.25% | 1.29% | 1.38% | 1.45% | 1.02% | 0.92% | 1.25% | 0.79% |
| Growth in international trade | 1.44% | 1.50% | 1.56% | 1.66% | 1.24% | 1.13% | 1.43% | 0.96% |
| 100 year depreciation of investments | 1.07% | 1.10% | 1.18% | 1.23% | 0.89% | 0.80% | 1.07% | 0.72% |
| 30 year depreciation of investments | 0.54% | 0.55% | 0.61% | 0.59% | 0.50% | 0.45% | 0.60% | 0.40% |
| Myopia | 1.26% | 1.31% | 1.39% | 1.47% | 1.03% | 0.93% | 1.24% | 0.83% |
| Land in production function | 1.49% | 1.54% | 1.63% | 1.73% | 1.24% | 1.12% | 1.47% | 0.99% |
| Formal sector wage data | 1.07% | 1.10% | 1.18% | 1.27% | 0.85% | 0.76% | 1.08% | 0.71% |
| $\frac{1}{\nu} = 2$ | 1.25% | 1.29% | 1.38% | 1.46% | 1.03% | 0.92% | 1.23% | 0.82% |
| $\frac{1}{\nu} = 4$ | 1.27% | 1.31% | 1.40% | 1.47% | 1.04% | 0.93% | 1.25% | 0.83% |
| $\sigma = 9.28,\ \eta = 7.41$ | 1.54% | 1.60% | 1.68% | 1.77% | 1.32% | 1.19% | 1.54% | 1.03% |
| $\sigma = 16.6,\ \eta = 7.1$ | 1.51% | 1.57% | 1.64% | 1.74% | 1.28% | 1.15% | 1.47% | 0.99% |
| Stationary equilibrium 200 years | 1.26% | 1.30% | 1.39% | 1.47% | 1.03% | 0.93% | 1.24% | 0.83% |
| Stationary equilibrium 400 years | 1.26% | 1.30% | 1.39% | 1.47% | 1.03% | 0.93% | 1.24% | 0.83% |

*Notes: The table compares aggregate welfare gains versus the status quo road investments for counterfactual allocations of road upgrades. The percentage change in welfare is measured in terms of consumption equivalent variation. 'Maximize market potential' counterfactuals refer to counterfactuals based on maximizing pairwise market potential. 'Maximize market access' counterfactuals refer to counterfactuals based on maximizing the welfare contribution of road investments via endogenous improvements in market access. Inundation scenario incorporates a 1 meter rise in the sea level realized gradually over 100 years. No inundation scenario assumes that sea levels will remain at current levels*