The London School of Economics and Political Science

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

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Declaration

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Abstract

Coasts contain a disproportionate share of the world's population, reflecting historical advantages, but environmental change threatens a reversal of coastal fortune in the coming decades as natural disasters intensify and sea levels rise. This thesis considers whether large infrastructure investments should continue to favour coastal areas. I use a dynamic spatial equilibrium framework and detailed georeferenced data from Vietnam to examine this issue and find evidence that coastal favouritism has significant costs. Road investments concentrated in coastal regions between 2000 and 2010 had positive returns but would have been outperformed by allocations concentrated further inland even in the absence of sea level rise. Future inundation renders the status quo significantly less efficient. Under a central sea level rise scenario, welfare gains 72% higher could have been achieved by a foresighted allocation avoiding the most vulnerable regions. The results highlight the importance of accounting for the dynamic effects of environmental change in deciding where to allocate infrastructure today.

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1 Chapter 1: Introduction

This thesis considers the links between the environment, trade and development as mediated through transport infrastructure investments. A growing literature shows how these investments influence trade costs and hence the distribution of economic activity across space and aggregate growth (Redding and Turner (2015), Allen and Arkolakis (2016), Fajgelbaum and Schaal (2017)). The pattern of gains may, however, be fundamentally affected by a changing environment. 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 georeferenced micro-data to analyse whether infrastructure investments should continue to favour 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 metres 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)).

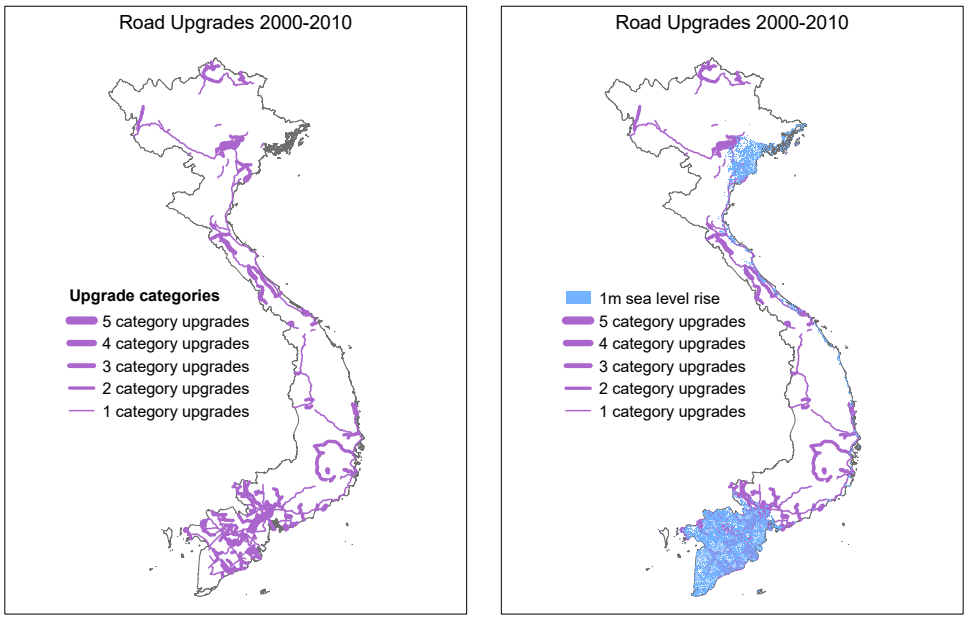
Globally, however, coasts continue to attract a large and growing share of major infrastructure investments. I focus on transport infrastructure investments, a significant area of spatial policy accounting for annual spending

of over $900bn (Oxford Economics (2015)).[1] 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 thesis is to consider whether such significant investments in the LECZ represent misallocation, taking into account both their effect 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 favour 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.

[1] Transport infrastructure investments are one of a wide range of spatially-targeted policies and investments that have been discussed in the literature, including tax incentives (Gaubert (2018)), zoning and building regulations (Glaeser and Gottlieb (2008)), regional development programmes (Kline and Moretti (2014)) and special economic zones (Wang (2013)).

Figure 1: Road investments in Vietnam, 2000-2010



I first present reduced form evidence that road investments in this setting were associated with local increases in economic activity. The empirical strategy is based on the construction over the study period of the Ho Chi Minh National Highway following the route of the Vietnam War era Ho Chi Minh Trail, which provides a segment of the upgraded network with a predetermined historical origin. The results are consistent with road upgrades attracting or creating economic activity in Vietnam over this period, in line with the findings of a large empirical literature in other contexts (reviewed in Redding and Turner (2015)) but in contrast to more mixed recent evidence on the effects of highway construction in neighbouring China (Faber (2014), Baum-Snow et al. (2016)).

In the context of infrastructure investments, moving beyond local effects is essential. To do this, I develop a dynamic, multi-region spatial equilibrium model. This approach allows me to estimate the complex general equilibrium impacts of transport infrastructure improvements and thus to quantify aggregate welfare effects and study policy counterfactuals. 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 both trade and migration, consistent with evidence of frictions in both goods and labour markets in my empirical setting (Anh (1999)). Households are forward looking and choose where to supply their labour each period, according to a dynamic discrete choice problem building on approaches in Artuç et al. (2010) and Caliendo et al. (2018) that takes into account heterogeneous worker preferences across locations. The production structure builds on seminal models in the new economic geography literature (Krugman (1991b), Helpman (1998), Redding (2016)), incorporating agglomeration externalities and international trade. I use variation from construction of the Ho Chi Minh National Highway to document that the effects of road upgrades, via their effect on district-level market access, are consistent with the model's predictions.

This setup allows me to model dynamic spatial adjustments as transport investments alter trade costs and future sea level rise inundates land and roads.[2] By incorporating the dynamic effects of infrastructure investments, as well as an environmental damage function, I am able to analyse 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 calibrate the model by using district-level data on the distribution of economic activity in 2010 to solve for relative productivity levels across districts. The calibrated values are strongly positively correlated with out-of-sample measures of productivity at the district level. Combining the calibrated values with projections of how future inundation will alter land areas and trade costs as sea level rise takes effect, I then solve the model

[2]Desmet et al. (2018) 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. (2018), this thesis 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.

for each location's equilibrium path of wages and employment and the net present value of welfare.

I quantify the gains from the road upgrades made in Vietnam from 2000 to 2010 by simulating the effects of their removal on the evolution of the economy. I find that the net present value of aggregate welfare was 1.74% higher as a result of the road upgrades than it would have been if no upgrades had been made. This estimate incorporates both the utility-enhancing effect of market access improvements via lower prices, higher wages and endogenous migration responses, and the detrimental effects of future inundation. To disentangle these effects, I re-simulate the model in a scenario with no future sea level rise. This reveals that the realised road upgrades would have yielded welfare gains of 2.49% in the absence of sea level rise, with immigration and welfare gains concentrated in coastal regions. The sharply lower welfare gains in the presence of sea level rise reflect the significant share of upgraded roads that are lost to inundation or that connect inundated areas. The discrepancy highlights the importance of considering dynamic environmental changes in assessing the gains from current investments.

The strong coastal concentration of the realised upgrades raises the question of whether alternative investment allocations may have been more efficient in a dynamic context where coastal regions face the prospect of future inundation. To examine this, I estimate whether higher welfare gains could have been achieved by a series of alternative road investments of the same total cost but allocated according to objective rules used by transport planners in other contexts. The first two counterfactuals are constructed without reference to future sea level rise: one focuses on highway connections between all major administrative divisions, while the second allocates upgrades between district pairs in order of decreasing market potential, a distance-weighted measure of market size. I also consider two allocation rules that take explicit account of the future effects of climate change. The first of these maximises market potential only outside regions that are projected to face inundation over the next century (the sub-1m LECZ), and the second

avoids the broader area projected to be affected by more severe storm surges, flooding and saltwater intrusion (the sub-5m LECZ). The simulations suggest that the realised road upgrades favoured coastal regions relative even to the counterfactual allocations that do not take vulnerable areas into consideration: all of the counterfactuals induce long-term population declines in the LECZ relative to the status quo.

The principal finding of the thesis is that, under central sea level rise scenarios, this coastal favouritism had significant costs. Welfare gains 72% higher than those achieved by the realised upgrades are available from the allocation maximising market potential outside the sub-1m LECZ. The unconstrained market potential maximising allocation and the allocation maximising market potential outside the sub-5m LECZ also achieve higher welfare gains (64% and 29% respectively) than the status quo, although the latter does outperform the allocation connecting major administrative divisions (9% lower gains).

The model also allows me to analyse how far the inefficiency in the realised allocation is driven by future inundation. To estimate this, I simulate all counterfactuals in a scenario without future sea level rise. The results highlight that significant relative gains would have been available even in the absence of sea level rise. In this case, gains of 55% and 48% relative to the status quo are achieved by the counterfactuals maximising market potential and maximising market potential outside the sub-1m coastal zone respectively. As such, the extent of coastal favouritism appears unwarranted even without accounting for future environmental change. This finding is consistent with the emergence of path dependence (Krugman (1991a), Bleakley and Lin (2012), Allen and Donaldson (2018)) as allocation decisions fail to keep pace with changing coastal advantage or reflecting policy myopia (Nordhaus (1975), Rogoff (1990), Rodrik (1996)). Comparing the two sets of simulations reveals that future sea level rise strongly accentuates the gains from allocating infrastructure investments away from the most vulnerable regions.

I use the model to examine key alternative explanations that might plausibly help to rationalise the observed coastal favouritism in road upgrades. I consider the fact that Vietnam's residents might attach an increasing amenity value to coastal proximity as development proceeds, by re-simulating the model assuming that the coastal premium reaches developed country levels within 100 years. I estimate the effect of allowing secular trends in district-level productivities observed over the last decade to continue. I re-simulate the model assuming that the high rates of export growth experienced in recent years continue for another 50 years. In all cases, the key findings that there is over-investment in coastal areas with or without sea level rise, and that under central sea level rise scenarios the highest gains are achieved by an allocation avoiding the most vulnerable regions, are robust.

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 thesis 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 thesis highlight that it will be crucial to ensure that these allocations take account of the dynamic effects of future environmental change.

This thesis proceeds as follows. Chapter 2 describes the data used in the paper and presents a series of motivating facts in my empirical setting. Chapter 3 introduces the quantitative spatial model used to study the general equilibrium effects of road upgrades. Chapter 4 describes the estimation procedure used to solve the model and conduct counterfactual analyses. Chapter 5 quantifies the dynamic welfare gains from the realised

road upgrades made in Vietnam between 2000 and 2010 by simulating the effects of their removal. Chapter 6 presents the results of simulating a series of policy counterfactuals. Chapter 7 concludes.

2 Chapter 2: Data and motivating facts

This chapter describes the data used in the analysis and presents motivating evidence from Vietnam. I document descriptive statistics consistent with changing coastal advantage in Vietnam. I then present evidence from the data that road investments made in this setting from 2000-2010 were strongly concentrated in coastal regions. Finally, I present reduced form evidence that the location of these investments was important for the distribution of economic activity using an instrumental variables strategy based on highway construction along the route of the historic Ho Chi Minh Trail during my study period.

2.1 Data

The primary geographic units used in the analysis are 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. The mean spatial unit area is 601km^2.[3]

The analysis requires geographic, demographic, economic and transport data for each spatial unit. Conducting the analysis at such a fine level of spatial disaggregation helps to capture localised regional disparities in these variables and reduces potential problems inherent in multi-region spatial models that treat population and economic activity within each unit as if they were located at a single point. While most data are available at the district level, small area estimation is required to obtain expenditure per capita data at this level and some approximations are needed to assign an

[3]This is somewhat smaller than the spatial units used in other empirical studies (e.g. US counties), consistent with evidence that agglomeration economies attenuate rapidly across space, e.g. Rosenthal & Strange 2003, Jae et al 1993.

origin district to internal migrants within their province of origin (described below). To check that these factors are not driving the results, I also conduct the analysis at the province level (at which all data are representative) and obtain qualitatively similar results.

2.1.1 Geographic data

I assign the location of each unit to the latitude and longitude of its centroid. Land areas are calculated using GIS data on land area without permanent ice and water at a resolution of 30 arc-seconds from the Gridded Population of the World (GPW) version 4 dataset of the Center for International Earth Science Information Network (CIESIN) at Columbia University. Digital elevation data at a resolution of 3 arc-seconds is obtained from the NASA Shuttle Radar Topographic Mission dataset of the Consultative Group on International Agricultural Research's Consortium for Spatial Information. Land cover data is obtained at a resolution of 15 arc-seconds from the US Geological Survey. District-level data on average precipitation, temperature and the percentage of the district's area that is cultivated, forested or bare/rocky is from Miguel and Roland (2011).

2.1.2 Demographic data

The population of each spatial unit in 2010 is calculated using the GPW dataset, which uses district-level data from the 2009 Population Census. Population data by district in 1999 is available for most districts from Miguel and Roland (2011), and extrapolated data is available for all districts from the GPW dataset.

IPUMS International provides data on internal migration from a 15% sample of the 2009 Population and Housing Census (IPUMS (2015)). The census questionnaire includes questions on the respondent's current province and district of residence; whether the respondent migrated within district, within province, across provinces or abroad within the last five years; and the respondent's 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.[4]

This data can be used directly to obtain internal migration flows at the province level. However, data is not available on the origin *district* of internal migrants, which is needed for analysis at the district level. For this 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.

2.1.3 Economic data

Calibration of the model requires wage data for each spatial unit. I run the calibrations separately using two sources of wage data. The first is the Vietnam Enterprise Census (VEC), which has the advantage of being a census but the shortcoming that most small and informal sector firms are excluded. The second is the Vietnam Household Living Standards Survey (VHLSS), which provides more comprehensive data on surveyed individuals' formal and informal income sources, as well as expenditure per capita, but the raw data is at best representative at the province level.

The VEC has been conducted annually by the General Statistics Office of Vietnam since 2000. The census provides firm-level data covering all economic units with their own legal status, independent business accounts and more than 10 employees. Primary, manufacturing and services industries are included, and the data collected includes firm ownership, industry, location, age, employees, employees' compensation and fixed capital. There are a total of 42,044 firm-level observations in 2000 and 287,853 observations in

[4]International migrants are excluded from the analysis, consistent with the model's assumption of immobility of labour between countries (see Chapter 3). 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.

2010. The total reported labour force employed by these firms represented 4% and 11% of the total population in 2000 and 2010 respectively. Each firm for which data is reported in the VEC is assigned to a spatial unit based on its province and district identifiers. For each firm, I calculate the average annual wage per worker as the sum of salaries and salary equivalents paid to all workers divided by the number of workers. Each spatial unit average wage is then obtained as the mean value across all firms in the spatial unit, excluding 1% outliers.[5]

The VHLSS has been conducted biennially by the General Statistics Office of Vietnam since 2002. These surveys collect information on demographics, education, health, employment, income, consumption, housing and participation in poverty alleviation programmes. In each round, some respondents are administered the full survey questionnaire (29,530 households in 2002, 9,402 in 2010) and a larger number of respondents are administered a shorter version excluding the expenditure module (75,000 households in 2002, 69,360 in 2010). Responses to the former are representative at the level of Vietnam's six geographic regions and for rural/ urban areas, while those to the latter are representative at the provincial level (GSO (2010a), Lanjouw et al. (2013)). Lanjouw et al. (2013) estimate province- and district-level expenditure per capita using small area estimation techniques combining the VHLSS data with population census data, and Miguel and Roland (2011) report similar estimates for 1999. The baseline specifications are run using these data, since consumption data are often preferred to income data in developing countries in light of evidence that the former may be more accurate and closely linked to permanent income (e.g. Ravallion (1994), Glewwe et al. (2002)). The results are robust to instead using the formal sector wage from the VEC, as shown in Chapter 6.

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

[5]Very similar results are obtained using the median wage across all firms in the spatial unit

I use district-level data on poverty rates in 2009 from the World Bank's mapVIETNAM dataset, and on 1999 poverty rates, literacy rates and urban shares from Miguel and Roland (2011).

2.1.4 Transport network data

The analysis requires data on the location of transport infrastructure in 2000 and 2010, and bilateral transport costs between each pair of spatial units based on these networks.

I map Vietnam's road, inland waterway and coastal shipping networks in 2000 and 2010 using manually digitized data described at Appendix A.[6] This Appendix also describes the data used to assign to each stretch of the network in both years a direct economic cost of transportation per ton-km (to represent, for instance, fuel costs) and a travel time cost associated with time spent in transit. For each mode of transport used along a route, I also assign a one-off mobilisation 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 mobilisation 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.

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

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

from GSO (2005) and GSO (2010b), and averaging using weights given by the share of each commodity in 2008 inter-provincial freight traffic demand from JICA (2010). I allow movement between different types of road and the inland waterway network wherever they connect (albeit incurring the relevant mobilisation cost), but only allow switches on to or off coastal shipping routes at sea ports.

Based on these networks, I use the Network Analyst extension in ArcGIS (which employs the Dijkstra algorithm) to compute the bilateral trade cost along the lowest cost route between any two points on the transport network in each year.

Since the location of each spatial unit is assigned to its centroid, the Dijkstra algorithm would estimate that trade *within* each spatial unit is costless. Analyses that calibrate trade costs as a function of distance alone have addressed this problem by approximating intra-unit trade costs based on the average distance travelled to the centre of a circular unit of the same area from evenly-distributed points within it, given by $\frac{2}{3}\left(area/\pi\right)^{1/2}$ (e.g. Redding and Venables (2004), Au and Henderson (2006a)). Since my analysis focuses on changes in transport infrastructure, distance-based measures will not be appropriate. However, I use the same intuition that the average distance travelled from points inside a circular unit to its centre will be two thirds of the unit's radius. I assume that intra-unit trade occurs via road given the comparative advantage of road transport over shorter distances. For each spatial unit, I calculate both the travel cost along the road network and the geodesic distance from the unit's centroid to the nearest point at which the road network intersects the unit's border. I then scale the travel cost (net of the road mobilisation cost) by the ratio between the measured geodesic distance and the radius of a circle with the unit's total land area. I use two thirds of this value added to the road mobilisation cost as my estimate of the intra-unit bilateral trade cost.[7] I normalise the units of all

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

trade costs such that the lowest mobilisation cost in 2010 is equal to one.[8]

The travel cost from each spatial unit centroid to international markets is calculated as the travel cost from the centroid to the nearest international seaport[9] plus a fixed amount to account for the cost of shipping goods from an international port to foreign markets. To obtain the latter value, I use the estimate from Baum-Snow et al. (2016) that the cost of reaching foreign markets from international ports is approximately 15% of the average cost of reaching the port from interior locations.

2.1.5 Road construction costs

I calculate the construction costs of road upgrades following the methods used in Faber (2014) and Alder (2017). These use a construction cost function based on the engineering literature, which gives relative road construction costs for area cells on different terrains:

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

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 (1) 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 the land cover data described above.

In order to convert the units of equation (1) into constant 2010 US$ per km, I use data on the average cost per km of road rehabilitation and upgrade

costs as along class 1 waterways.

[8]This normalisation is chosen to ensure that no intra- or inter-unit iceberg trade cost under any counterfactual scenario in either year can fall below one. Intuitively, this implies that trade is costless if the lowest mobilisation cost is incurred but no distance is travelled along the network.

[9]The results are robust to assuming that international trade occurs via land border crossings of the Asian Highway Network as well as international seaports.

from Mladenovic et al. (2013), based on 161 Government of Vietnam and World Bank contracts from 2004-2013. I use equation (1) to calculate the average cost per km of realised road upgrades from 2000 to 2010 in units of the equation, and use this with the average cost per km of road upgrades in constant 2010 US$ to calibrate the units of equation (1) to constant 2010 US$. The construction costs of an arbitrary counterfactual network of road upgrades can then be calculated using equation (1) and the same conversion rate between units of this equation and constant 2010 US$.

2.2 Changing coastal advantage in Vietnam

Vietnam is historically a highly agrarian economy, with settlement concentrated in the low elevation fertile flood plains of the Red River and Mekong River deltas and coastal harbours (Falvey (2010), Forbes (1996)). As shown in Figure 2, the population in 2000 remained strongly concentrated in the delta regions and along the eastern sea coast. Consistent with this, the country's sub-10m LECZ[10] is home to a strikingly large share of its population by global standards: in 2000, it contained the fourth largest population (43 million) and population share (55%), the tenth largest land area (66,000km^2) and the ninth largest land share (20%) (McGranahan et al. (2007)).

While historically important, the LECZ has been on a trajectory of decline in recent decades. The country has experienced drastic structural change following a wide-ranging series of economic reforms ('Doi Moi'[11]) 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 distribution of employment away from the coast and deltas towards less agrarian regions

[10]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.*

[11]The 'Doi Moi' ('Renovation') programme 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.

(as shown in Figure 3) and a commensurate 4 percentage point decline in the sub-5m LECZ's population share from 2000 to 2010. Wage growth has also been slower than the country average in the sub-5m LECZ, where the formal sector wage increased by a population-weighted average of 97% versus a country average of 118%. The corresponding increases for expenditure per capita were 177% and 183% respectively.

Vietnam's LECZ is also highly and increasingly vulnerable to natural disasters and rising sea levels. Vietnam ranks eighteenth in the World Risk Index of natural disaster risk across countries (Birkmann et al. (2014)). The LECZ is particularly susceptible to cyclones and flooding (as shown in Figure 4), which together accounted for 90% of natural disaster events and 94% of deaths from 1900-2015 (Guha-Sapir et al. (2015)). The beginning of my study period in 2000 succeeded 1997's Typhoon Linda, which killed more than 3000 and destroyed over 300,000 houses in the Mekong River Delta, and preceded three consecutive years of flooding in the same region that killed nearly 1000 (Nguyen et al. (2007)).

Looking ahead, Vietnam is among the top five countries globally likely to be affected by climate change, with increasing high-intensity typhoons and sea level rises of 57-73cm projected by 2100 (Thao et al. (2014)). Under a 1m sea level rise, 5% of Vietnam's land area and 38% of the Mekong River Delta would be inundated (GFDRR (2015), ICEM (2009)). Compounding this, urbanisation and infrastructure development in low-lying regions are also responsible for depleting natural defences and exacerbating vulnerability to disasters (Turner et al. (1996)).

2.3 Road investments in Vietnam from 2000-2010

Despite the trends described in the previous section, Vietnam's development strategy continues to favour the growth of urban areas in coastal and low-lying regions (DiGregorio (2013)). This thesis focuses on transport infrastructure investments, an important dimension of spatial policy in Vietnam as in other developing country contexts. 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 5 shows road maps of Vietnam at the beginning and end of the study period. While the total length of the road network increased by only 0.6%, there were significant upgrades of the existing network from secondary roads (minor and other roads, whose total length declined by 15%) to main roads (freeways, dual carriageways and major roads, whose total length increased by 156%).

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% and that of secondary roads declined by 26%. Even after controlling for land area and population, districts in the sub-5m LECZ experienced differential road improvements, as shown in Table 1.

The starting point for the analysis is that this targeting of road investments towards coastal areas may have important implications for the welfare gains that these investments confer, especially in a dynamic context in which the environmental vulnerability of coastal regions is changing. The first step in the analysis is to document that road investments are important for the distribution of economic activity across space in this context. The reduced form analysis in the next section uses a segment of the upgraded network with a predetermined historical origin to present evidence consistent with upgraded roads attracting or creating economic activity in Vietnam over my study period. In Section 3, I then develop a quantitative spatial model to account explicitly for the general equilirbrium effects of transport improvements in order to distinguish reallocation from growth and estimate aggregate welfare effects.

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

2.4 Reduced form effects of road investments

The effect of transport improvements on economic activity is the subject of a growing empirical literature, reviewed in Redding and Turner (2015). While several studies identify positive effects on local economic activity in both developed (for example, Chandra and Thompson (2000) and Michaels (2008)) and developing (for example, Donaldson (2018) and Banerjee et al. (2012)) countries, recent studies of the effects of highway connections in China document zero or even negative effects (Faber (2014), Baum-Snow et al. (2016)). Establishing the sign of this relationship in the reduced form in Vietnam is important in understanding the effects of road upgrades and determining whether a spatial equilibrium model which assumes positive economic impacts of local trade cost reductions is a sensible basis for structural analysis in this setting. This section aims to provide empirical evidence on the causal effects of transport improvements in Vietnam, a setting that has received very little attention in this literature.

2.4.1 Empirical strategy

I estimate the effect of road upgrades on local economic outcomes using a difference-in-difference specification given by:

$$\triangle ln\, y_i = \beta ln\ proximity_i + \gamma X_i + \delta_r + \varepsilon_i \tag{2}$$

The dependent variable $\triangle ln\, y_i$ is the change in an outcome of interest (district-level log expenditure per capita or log population) in district i between 2000 and 2010. $ln\ proximity_i$ is the log proximity (inverse of distance) of each district centroid to the nearest stretch of upgraded road, where proximity is weighted by the number of categories by which the stretch is upgraded. This yields a continuous variable with a non-zero value for all districts.[13] X_i is a vector of district-level control variables, described be-

[13]Qualitatively similar results are obtained using (i) the weighted length of road upgrades made in district i from 2000 to 2010, where a weight of one is assigned to stretches

low, and δ_r are regional fixed effects. Standard errors are clustered at the province level.

Non-random assignment of transport infrastructure precludes estimation of equation (2) using ordinary least squares. To address problems associated with endogenous road placement, I propose an instrument for road upgrades received from 2000-2010 based on the Government of Vietnam's announcement of a highway project to be built along the route of the historic Ho Chi Minh Trail from 2000.

The Ho Chi Minh Trail was the North-South supply route used by the Viet Cong and North Vietnamese Army during the Vietnam War. I construct the instrument using the log proximity of each spatial unit centroid to the nearest point on the trail route from 1969-73, manually georeferenced from maps in Morris (2006).[14] This was the key period of the trail's operation after the coastal supply route became unusable in 1968 and before cessation of US aerial bombing in 1973. I restrict attention to those spatial units below the median distance from the trail (shown in Figure 6) given expected non-monotonicities in the relationship between proximity to the trail and road upgrades received.[15]

The relevance of the instrument rests on the announcement in 1997 of construction of the Ho Chi Minh National Highway along the route of the trail. Construction began in 2000 with an initial proposed construction timeline of four years and length of nearly 2,000km. The project represented Vietnam's largest domestically-financed infrastructure project and is widely regarded as a largely politically-motivated project (e.g. Financial Times

upgraded by one category, two to stretches upgraded by two categories and so on; and (ii) the log weighted density of road upgrades within 50km of the district centroid, to account for the fact that districts may benefit from transport improvements in neighbouring areas.

[14]In robustness specifications where the endogenous dependent variable is the weighted length of road upgrades in (or within 50km of) each district, the instrument used is instead the length contained within each spatial unit of the trail route from 1969-73.

[15]The results are robust to not imposing this restriction. The restriction is imposed in the preferred specification given the likelihood that a concentration of road upgrades along the trail may be expected to displace alternative road upgrades nearby, while more distant districts too far away to benefit from market access improvements along the trail may be more likely to receive compensating alternative road upgrades.

(1997)): the historical and patriotic rationale for building the highway along the route of the historic trail has been emphasised alongside its aim to encourage growth in the west of Vietnam. Although it follows the route of the trail in large part, several new stretches have been added (Morris (2006)). Given the targeting, scale and timing of highway construction, the route of the historical trail should be a relevant instrument for road upgrades made between 2000 and 2010.

The exclusion restriction requires that, conditional on controls and regional fixed effects, the instrument should affect the outcome variables only through its effect on road upgrades made between 2000 and 2010. The trail was constructed during the Vietnam War to provide a logistical supply route to carry soldiers and machinery between North and South that was less susceptible to US aerial bombing than the coastal Route 1. Exogeneity of the instrument therefore requires that routes chosen for the purposes of avoiding US aerial bombing from 1969-1973 should not be systematically related to factors that affect economic or population growth from 2000-2010 other than through the increased probability of receiving road upgrades over this period. Lending credence to this, the trail route was chosen to be less visible from the air, protected by mountainous low-lying cloud and fog, with fewer wide rivers to cross and more materials available to repair damage than along Route 1 (Morris (2006)). Importantly, this military mandate did not include reference to future population growth or economic development in the regions it traversed.

The inclusion of an appropriate set of controls is clearly important given that we may expect some of the physical characteristics that made the trail route attractive as a disguised supply route (higher elevation, being further from the coast, etc) to affect contemporary economic growth, and that the trail was subject to particularly acute war damage. The district-level control variables included are as follows.

The first set of control variables included relate to physical geography. These are important given that the Ho Chi Minh Trail was chosen to fol-

low rugged, mountainous terrain in order to avoid aerial bombing, and such factors may affect suitability for modern economic growth or desirability as an internal migration destination. To address this possibility, I include controls for the mean elevation and slope of each district, log distance from the district's centroid to the coast, log district land area, average precipitation and temperature and the percentage of the district's area that is cultivated, forested or bare/ rocky. In light of the trail's aim to connect North and South, I also control for the log distance from each district to Hanoi or Ho Chi Minh City (the capital cities of erstwhile North and South Vietnam and Vietnam's major metropoles today), which may be expected to affect present-day growth trajectories.

Another potential concern arises from the fact that areas surrounding the Ho Chi Minh Trail were subject to particularly heavy aerial bombardment during the war. This could plausibly affect economic growth from 2000-2010 through, for instance, its effects on the destruction of physical infrastructure or remaining unexploded ordnance (Miguel and Roland (2011)). I therefore control for US and allied ordnance expended during the Vietnam War using Miguel and Roland (2011)'s district-level data on the total intensity of bombs, missiles and rockets, the primary measure used in their analysis given its substantial correlation with other ordnance categories.

Finally, I add controls to allay concerns that districts along the trail route are systematically different in terms of pre-existing economic conditions and political status. This may be of particular concern given the Ho Chi Minh Highway's second aim (alongside its historical and patriotic importance) to foster growth in poorer remote regions in the west of the country. The first is a dummy variable denoting whether the district contains a province capital. I also include the log district population in 2000, the literacy rate, poverty rate and urban share in 1999, the proportion of the population working in the formal sector in 2000 and the log efficiency units of roads in the district.[16]

[16]The efficiency units of roads is calculated by assigning to each stretch of road a weight of one for freeways and for all other road types a weight given by the ratio of average speed (across all slopes) on that road type relative to freeways in 2010.

Table 2 presents summary statistics of all variables used in the regressions.

2.4.2 Results

The reduced form results shown in Table 3 reveal that log proximity to the Ho Chi Minh Trail, conditional on controls, is positively correlated with local increases in per capita expenditure from 2000 to 2010, with a 1% increase in weighted proximity to the trail associated with a 2.9% increase in per capita expenditure over the period. Reassuringly, a 'placebo' specification finds no such correlation between proximity to the trail and local increases in per capita expenditure in a period pre-dating construction of the Ho Chi Minh National Highway from 1993 to 1998.[17]

The first stage results in which $ln\ proximity_i$ is regressed on the instrument are shown in Table 4. The instrument is a strongly significant predictor of the endogenous variable conditional on the full set of controls and the F-statistic exceeds the common threshold for weak instruments formalised in Staiger and Stock (1997).

Table 5 reports the OLS and second stage IV results estimating the effects of road upgrades on local economic activity. The IV results in the first panel suggest that a 1% increase in weighted proximity to an upgraded road on average increased district-level expenditure per capita between 2000 and 2010 by a statistically significant 3.4%. The OLS estimates are imprecisely estimated but the point estimates are smaller than the IV estimates, suggesting that declining regions may have been favoured with more road improvements. This is in line with the aims of the Ho Chi Minh National Highway to encourage growth in less developed regions in the west of Vietnam (and with countercyclical road building in other contexts, e.g. Duranton and Turner (2012)). The results are robust to weighting the regressions by the initial value of the relevant dependent variable, allaying concerns that the results may be driven by outliers with low initial values. The placebo

[17] Data from this pre-period is only available for 63 of the 263 districts considered in the main reduced form analysis. Both the reduced form and IV results for the 2000-2010 period remain significant in this subset of districts. Results are available on request.

specification from 1993 to 1998 again finds no evidence of pre-trends before construction of the Ho Chi Minh National Highway began.

The results in the second panel of Table 3 and Table 5 suggest that local road upgrades had no significant effect on local population. This is unsurprising given that data on population changes are limited to the same period as that over which road upgrades are measured, which reduces the likelihood of observing significant effects relative to studies which consider effects over longer time periods (Duranton and Turner (2012)) or with a lag (Faber (2014)).[18]

The results are consistent with regions that are closer to road upgrades over this period - and hence which may be expected to see the largest declines in trade costs - also experiencing the greatest increases in local economic activity. This suggests that the strong concentration of road upgrades in Vietnam's coastal zone may in turn have increased the concentration of economic activity in the country's coastal regions. These estimates do not, however, capture general equilibrium effects or reveal whether increases in activity near road upgrades represent a reallocation of activity from elsewhere or aggregate growth. Such a distinction is necessary to be able to estimate the welfare impacts of investments and evaluate policy counterfactuals. To facilitate such analyses, the next chapter develops a general equillibrium spatial model.

[18]This finding is also consistent with the model's prediction that road upgrades should not affect the contemporaneous population distribution, although they are expected to attract population in future periods (see Chapter 3).

3 Chapter 3: Theoretical framework

This chapter describes the model used to estimate the effects of both realised and counterfactual road upgrades in Vietnam as the climate changes.

The framework used is a multi-region quantitative spatial equilibrium setup. In contrast to reduced form approaches, this framework captures general equilibrium effects and thus permits measurement of the aggregate welfare impacts of policy interventions. While the spatial equilibrium literature has to date focused predominantly on static models, this thesis 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 developed in Artuç et al. (2010) and Caliendo et al. (2018).

There is an initial distribution of agents across markets, who in the first period earn and consume consumption goods and land in their origin location. Agents are forward-looking, and each period choose their location for the next period optimally based on the projected future path of real wages and amenities in, and their idiosyncratic taste shocks for, each location, net of the migration cost between regions.

Firms in each location use labour to produce horizontally-differentiated goods varieties in proportion to the endogenous labour supply in that location each period. Production occurs under conditions of monopolistic competition and increasing returns to scale. Bilateral goods trade between each pair of locations, and between each location and foreign markets, is subject to iceberg trade costs. These trade costs in turn depend on the transport network each period. The production setup gives rise to agglomeration externalities[19], since increased concentration of population in a location expands the measure of varieties produced there, which given costly trade and consumer love of variety makes the location more attractive. Offsetting

[19] An empirical literature finds that agglomeration externalities, as well as exogenous locational characteristics, play an important role in determining location choice (Starrett (1978), Rosenthal and Strange (2004)).

these, each location's fixed supply of residential land acts as a dispersion force, since increased concentration of population in a location bids up land prices.

Given data on the distribution of the population, wages and trade costs in an initial period, the model can be inverted to obtain the distribution of productivities across regions that rationalises the observed data as an equilibrium outcome. With these calibrated productivities and data on how land areas and trade costs evolve over time, the model can then be solved for each location's equilibrium path of wages and employment and the net present value of welfare.

The setup of the model thus allows me to estimate the effect of road upgrade investments and future inundation on the evolution of Vietnam's economic geography and aggregate welfare. Intuitively, road upgrade investments that reduce the cost of a given location trading with large markets with few trading partners increase that location's market access and reduce its price index, increasing local equilibrium employment. The effects of inundation in the model are twofold: inundation of roads increases trading costs and inundation of land pushes up land rents, reducing local equilibrium employment.

The following sections describe the model setup in detail and derive the equilibrium conditions. I then use variation from the Ho Chi Minh Trail as introduced in Chapter 2 to test whether the effects of road upgrades in my empirical setting are consistent with the predictions of the model.

3.1 Model setup

The economy consists of several locations indexed by $i, n \in N$ over discrete time periods $t = 0, 1, 2, ...$ Locations differ in terms of their productivity $A_{n,t}$, amenity value $B_{n,t}$, supply of (immobile) land $H_{n,t}$ and initial endowment of (imperfectly mobile) workers $L_{n,0}$.

The productivity terms $A_{n,t}$ represent features that make different regions more or less attractive in terms of the costs of production, which may

include natural advantages (such as proximity of natural resources) or induced advantages (such as infrastructure). Local amenities $B_{n,t}$ capture characteristics of each location that make them more or less desirable places to live.

3.2 Consumer preferences

Workers are each endowed with one unit of labour 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 rate $\beta \in (0, 1)$. 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 a migration cost, which depends on the locations of origin and destination according to the bilateral cost matrix μ_{ni}, which is assumed time-invariant.[20] This migration cost term contributes to persistence in location choice, since workers incur a utility cost of relocating to any location other than their location of origin. Labour is immobile across countries.

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

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

where $0 < \alpha < 1$.

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

The goods consumption index $C_{n,t}$ is defined over an endogenously-determined measure $M_{i,t}$ of horizontally differentiated varieties j supplied by each location, $C_{n,t} = \left[\sum_{i \in N} \int_0^{M_{i,t}} c_{ni,t}(j)^{\frac{\sigma-1}{\sigma}} dj\right]^{\frac{\sigma}{\sigma-1}}$, where σ is the elasticity of substitution between goods.

Following Artuç et al. (2010), the idiosyncratic preference shocks $b_{n,t}$ are assumed to follow a Gumbel distribution with parameters $(-\gamma\nu, \nu)$, where γ is Euler's constant. Based on this assumption, it is shown in Appendix C that the expected lifetime utility of a representative agent at 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:

$$\begin{aligned} V_{n,t} = \mathbb{E}\left(v_{n,t}\right) \quad = \quad & \alpha ln\left(\frac{C_{n,t}}{\alpha}\right) + (1-\alpha) ln\left(\frac{H_{n,t}}{1-\alpha}\right) \\ & + \nu ln \sum_{i \in N} \left(exp\left[\beta V_{i,t+1} - \mu_{in} + B_{i,t}\right]\right)^{\frac{1}{\nu}} \end{aligned} \tag{3}$$

where the expectation is over preference shocks.

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

$$m_{in,t} = \frac{\left(exp\left[\beta V_{i,t+1} - \mu_{in} + B_{i,t}\right]\right)^{\frac{1}{\nu}}}{\sum_{m \in N} \left(exp\left[\beta V_{m,t+1} - \mu_{mn} + B_{m,t}\right]\right)^{\frac{1}{\nu}}} \tag{4}$$

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

$$L_{n,t+1} = \sum_{i \in N} m_{ni,t} L_{i,t} \tag{5}$$

3.3 Production, prices and trade

Production is characterised by a static optimisation problem that can be solved for equilibrium wages and prices given the supply of labour 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 (e.g. Helpman (1998)). 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 labour as well as a variable cost that depends on productivity $A_{i,t}$ in the location.[21] The number of labour units required to produce $x_{i,t}(j)$ units of variety j in location i at time t is therefore $l_{i,t}(j) = F + \frac{x_{i,t}(j)}{A_{i,t}}$. Goods produced are imperfectly mobile across locations, with bilateral goods trade costs taking the iceberg form such that $d_{ni,t}$ units of a good must be shipped from location i for one unit to arrive in location n, where $d_{ni,t} \geq 1$ for $\forall i, n, t$. Increasing returns to scale in production and costly trade, combined with consumer love of variety, result in agglomeration economies in the form of pecuniary externalities.

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

$$p_{ni,t}(j) = \left(\frac{\sigma}{\sigma - 1}\right) \frac{d_{ni,t} w_{i,t}}{A_{i,t}} \tag{6}$$

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

Combining equation (6) with the zero profit condition, equilibrium employment of effective labour units for each variety is equal to a constant, $l_{i,t}(j) = \bar{l} = \sigma F$. Combining this in turn with the labour market clearing condition in each location, $\int_0^{M_{i,t}} l_{i,t}(j) dj = L_{i,t}$, the measure of varieties sup-

[21] In this setup, increasing returns are internal to the firm; however, Allen and Arkolakis (2014) derive an isomorphism between this setup and their model with external increasing returns arising as a result of, for instance, knowledge spillovers, labour market pooling and input sharing.

plied in each location at time t is proportional to the endogenous supply of labour units in that location: $M_{i,t} = \frac{L_{i,t}}{\sigma F}$. The consumption goods price index can then be expressed as:

$$P_{n,t}^{1-\sigma} = \left(\frac{\sigma}{\sigma - 1}\right)^{1-\sigma} \left(\frac{1}{\sigma F}\right) \sum_{i \in N} L_{i,t} \left(\frac{d_{ni,t} w_{i,t}}{A_{i,t}}\right)^{1-\sigma} \tag{7}$$

The CES expenditure function implies that the value of bilateral trade flows of variety j from location i to location n at time t is $X_{ni,t}(j) = c_{ni,t}(j) p_{ni,t}(j) = \alpha X_{n,t} P_{n,t}^{\sigma-1} p_{ni,t}(j)^{1-\sigma}$, where $X_{n,t} = \sum_{i \in N} \int_0^{M_i} p_{ni,t}(j) c_{ni,t}(j) dj$ is aggregate expenditure at n at time t. Aggregating across varieties, we obtain the gravity equation for the total value of bilateral trade flows from i to n at time t:

$$X_{ni,t} = \alpha X_{n,t} P_{n,t}^{\sigma-1} \int_0^{M_{i,t}} p_{ni,t}(j)^{1-\sigma} dj = \alpha X_{n,t} P_{n,t}^{\sigma-1} M_{i,t} p_{ni,t}^{1-\sigma} \tag{8}$$

This yields an expression for the share of location n's expenditure on goods produced in location i at time t:

$$\pi_{ni,t} = \frac{X_{ni,t}}{\sum_{k \in N} X_{nk,t}} = \frac{M_{i,t} p_{ni,t}^{1-\sigma}}{\sum_{k \in N} M_{k,t} p_{nk,t}^{1-\sigma}} = \frac{L_{i,t} \left(\frac{d_{ni,t} w_{i,t}}{A_{i,t}}\right)^{1-\sigma}}{\sum_{k \in N} L_{k,t} \left(\frac{d_{nk,t} w_{k,t}}{A_{k,t}}\right)^{1-\sigma}} \tag{9}$$

3.4 Income

Let $y_{n,t}$ be the nominal income per labour unit and $r_{n,t}$ the land rent at n at time t.[22] A worker who starts the period at n will then receive real income:

$$Y_{n,t} = \frac{y_{n,t}}{P_{n,t}^{\alpha} r_{n,t}^{1-\alpha}} \tag{10}$$

Following Redding (2016), I assume that expenditure on land in each

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

location is redistributed lump sum to workers in that location in proportion to their labour units[23], so that total income in each location is:

$$y_{n,t}L_{n,t} = w_{n,t}L_{n,t} + (1-\alpha)y_{n,t}L_{n,t} = \frac{w_{n,t}L_{n,t}}{\alpha} \tag{11}$$

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

$$r_{n,t} = \frac{(1-\alpha)y_{n,t}L_{n,t}}{H_{n,t}} = \frac{1-\alpha}{\alpha}\frac{w_{n,t}L_{n,t}}{H_{n,t}} \tag{12}$$

Given the agent's budget constraint, the indirect utility from the agent's consumption of goods varieties and land before migration decisions is $\alpha ln\left(\frac{w_{n,t}}{\alpha}\right) - \alpha lnP_{n,t} - (1-\alpha)ln\left(\frac{(1-\alpha)L_{n,t}}{H_{n,t}}\right)$. This implies that the expected lifetime utility of a representative agent in location n at time t in equation (3) can be expressed as:

$$\begin{aligned} V_{n,t} &= \alpha ln\left(\tfrac{w_{n,t}}{\alpha}\right) - \alpha lnP_{n,t} - (1-\alpha)ln\left(\tfrac{(1-\alpha)L_{n,t}}{H_{n,t}}\right) \\ &\quad + \nu ln\textstyle\sum_{i\in N}\left(exp\left[\beta V_{i,t+1} - \mu_{in} + B_{i,t}\right]\right)^{\frac{1}{\nu}} \end{aligned} \tag{13}$$

3.5 International trade

While the framework described above is amenable to incorporating inter- as well as intra-national trade, quantitative analysis in this case requires data on wages, population, land area and bilateral transport costs for all foreign as well as domestic trading partner regions. To circumvent this, I employ the convenient method outlined in Baum-Snow et al. (2016) in their exposition of the canonical model in Eaton and Kortum (2002) with trade both between countries and regions within countries, which requires only data on the total value of the country's international exports and bilateral trade costs from each region to the nearest international port.

[23] As discussed in Redding and Rossi-Hansberg (2017), this is a common assumption in the spatial equilibrium literature given the challenges for model tractability of allowing for a land market in which agents can buy and sell land.

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

$$\pi_{ni,t} = \frac{L_{i,t}\left(\frac{d_{ni,t}w_{i,t}}{A_{i,t}}\right)^{1-\sigma}}{\sum_{k\in N} L_{k,t}\left(\frac{d_{nk,t}w_{k,t}}{A_{k,t}}\right)^{1-\sigma} + L_{x,t}\left(\frac{d_{nx,t}w_{x,t}}{A_{x,t}}\right)^{1-\sigma}} \tag{14}$$

and the price index is now given by:

$$P_{n,t} = \frac{\sigma}{\sigma-1}\left(\frac{1}{\sigma F}\right)^{\frac{1}{1-\sigma}}\left[\sum_{i\in N} L_{i,t}\left(\frac{d_{ni,t}w_{i,t}}{A_{i,t}}\right)^{1-\sigma} + L_{x,t}\left(\frac{d_{nx,t}w_{x,t}}{A_{x,t}}\right)^{1-\sigma}\right]^{\frac{1}{1-\sigma}} \tag{15}$$

Combining these equations and substituting $\pi_{ni,t} = \frac{X_{ni,t}}{X_{n,t}}$ yields:

$$X_{ni,t} = \frac{L_{i,t}\left(\frac{d_{ni,t}w_{i,t}}{A_{i,t}}\right)^{1-\sigma}}{P_{n,t}^{1-\sigma}\sigma F\left(\frac{\sigma}{\sigma-1}\right)^{\sigma-1}} \cdot X_{n,t} \tag{16}$$

This equation can be used to derive expressions for total international imports I (the value of all trade flows from the rest of the world to domestic locations) and total international exports E (the value of all trade flows from domestic locations to the rest of the world) in time period t:

$$I_t = \frac{L_{x,t}\left(\frac{w_{x,t}}{A_{x,t}}\right)^{1-\sigma}}{\sigma F\left(\frac{\sigma}{\sigma-1}\right)^{\sigma-1}} \cdot \sum_{n\in N} d_{nx,t}^{1-\sigma}\frac{X_{n,t}}{P_{n,t}^{1-\sigma}} \tag{17}$$

$$E_t = \frac{X_{x,t}}{P_{x,t}^{1-\sigma}\sigma F\left(\frac{\sigma}{\sigma-1}\right)^{\sigma-1}} \cdot \sum_{i\in N} L_{i,t}\left(\frac{d_{xi,t}w_{i,t}}{A_{i,t}}\right)^{1-\sigma} \tag{18}$$

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

(indexed by x):

$$X_{i,t} \quad = \quad \sum_{n\in N} \frac{L_{i,t}\left(\frac{d_{ni,t}w_{i,t}}{A_{i,t}}\right)^{1-\sigma}}{P_{n,t}^{1-\sigma}\sigma F\left(\frac{\sigma}{\sigma-1}\right)^{\sigma-1}} \cdot X_{n,t} + \frac{E_t \cdot L_{i,t}\left(\frac{d_{xi,t}w_{i,t}}{A_{i,t}}\right)^{1-\sigma}}{\sum_{i\in N} L_{i,t}\left(\frac{d_{xi,t}w_{i,t}}{A_{i,t}}\right)^{1-\sigma}} \tag{19}$$

Following Donaldson and Hornbeck (2016)'s adaptation of Eaton and Kortum (2002), Baum-Snow et al. (2016) define a consumer market access term $CMA_{i,t} = P_{i,t}^{1-\sigma}$ and a firm market access term $FMA_{i,t} = \sum_{n\in N} \frac{X_{n,t}}{P_{n,t}^{1-\sigma}} d_{ni,t}^{1-\sigma} + \frac{X_{x,t}}{P_{x,t}^{1-\sigma}} d_{xi,t}^{1-\sigma}$. Substituting for $P_{n,t}$, $X_{n,t}$, I_t and E_t from above and imposing the assumptions that trade costs are symmetric (i.e. $d_{ni,t} = d_{in,t}$) and that imports equal exports, we obtain the result that:

$$CMA_{i,t} = FMA_{i,t} = MA_{i,t} = \sum_{n\in N} \frac{d_{ni,t}^{1-\sigma} X_{n,t}}{MA_{n,t}} + \frac{E_t d_{xi,t}^{1-\sigma}}{\sum_{k\in N} d_{xk,t}^{1-\sigma} \frac{X_{k,t}}{MA_{k,t}}} \tag{20}$$

.

3.6 General equilibrium

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

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

$$w_{i,t}L_{i,t} = \frac{L_{i,t}\left(\frac{w_{i,t}}{A_{i,t}}\right)^{1-\sigma} MA_{i,t}}{\sigma F\left(\frac{\sigma}{\sigma-1}\right)^{\sigma-1}} \tag{21}$$

2. Market access is given by:

$$MA_{i,t} = \sum_{n\in N} \frac{d_{ni,t}^{1-\sigma} w_{n,t} L_{n,t}}{MA_{n,t}} + \frac{E_t d_{xi,t}^{1-\sigma}}{\sum_{k\in N} d_{xk,t}^{1-\sigma} \frac{w_{k,t}L_{k,t}}{MA_{k,t}}} \tag{22}$$

3. Expected lifetime utilities satisfy:

$$\begin{aligned} V_{n,t} &= \alpha ln\left(\tfrac{w_{n,t}}{\alpha}\right) - \alpha lnP_{n,t} - (1-\alpha)ln\left(\tfrac{(1-\alpha)L_{n,t}}{H_{n,t}}\right) \\ &\quad +\nu ln\textstyle\sum_{i\in N}\left(exp\left[\beta V_{i,t+1} - \mu_{in} + B_{i,t}\right]\right)^{\frac{1}{\nu}} \end{aligned} \tag{23}$$

4. Migration shares satisfy:

$$m_{in,t} = \frac{\left(exp\left[\beta V_{i,t+1} - \mu_{in} + B_{i,t}\right]\right)^{\frac{1}{\nu}}}{\sum_{k\in N}\left(exp\left[\beta V_{k,t+1} - \mu_{kn} + B_{k,t}\right]\right)^{\frac{1}{\nu}}} \tag{24}$$

5. The evolution of labour units is given by:

$$L_{n,t+1} = \sum_{i\in N} m_{ni,t}L_{i,t} \tag{25}$$

Following Caliendo et al. (2018), a stationary equilibrium of the model is a sequential equilibrium such that $\{L_{n,t}, m_{ni,t}, w_{n,t}, MA_{n,t}, V_{n,t}\}_{t=0}^{\infty}$ are constant for all t.

3.7 Aggregate welfare

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

$$V_{n,t} = \sum_{s=t}^{\infty}\beta^{s-t}ln\left(\frac{\left(\frac{w_{n,s}}{\alpha}\right)^{\alpha}exp\left(B_{n,s}\right)}{P_{n,s}^{\alpha}\left(\frac{(1-\alpha)L_{n,s}}{H_{n,s}}\right)^{1-\alpha}\left(m_{nn,s}\right)^{\nu}}\right) \tag{26}$$

This welfare measure (and welfare changes induced by changes in fundamentals) may vary across locations. Aggregate welfare is the mean welfare

across all locations, weighted by their respective initial population shares:

$$W_t = \sum_{n \in N} \frac{L_{n,0}}{\sum_{i \in N} L_{i,0}} \left\{ \sum_{s=t}^{\infty} \beta^{s-t} ln \left(\frac{\left(\frac{w_{n,s}}{\alpha}\right)^{\alpha} exp\left(B_{n,s}\right)}{P_{n,s}^{\alpha} \left(\frac{(1-\alpha)L_{n,s}}{H_{n,s}}\right)^{1-\alpha} m_{nn,s}^{\nu}} \right) \right\} \tag{27}$$

3.8 Testing the model in the reduced form

The results of structural analyses are necessarily determined by the assumptions of the model used. While the literature has found empirical support for the mechanisms assumed in structural spatial equilibrium models in several studies using US data, there is much more limited - and mixed - evidence from developing countries.[24] In this section, I take two approaches to testing the predictions of the structural model in my empirical setting. In the first, I use variation from the Ho Chi Minh Trail as described in Chapter 2 to test whether the causal impacts of market access on local economic activity are consistent with the predictions of the model's gravity equation. I then test the model quantitatively by simulating the reduced form results predicted by the model and comparing these to the results yielded by the reduced form estimation.

3.8.1 Reduced form evidence for the gravity equation

The estimation is based on implementing the log-linear relationship between local wages and market access implied by equilibrium condition (21) as a regression, in a manner akin to Donaldson and Hornbeck (2016). I take logs of this equation and first difference, yielding:

$$\triangle ln\, w_i = \left(\frac{\sigma - 1}{\sigma}\right) \triangle ln\, A_i + \left(\frac{1}{\sigma}\right) \triangle ln\, MA_i \tag{28}$$

[24] Chauvin et al. (2017) find that the implications of the spatial equilibrium hypothesis, well documented in the USA, are rejected in India but not in China or Brazil. Gollin et al. (2017) do not find support for the predictions of a simple static spatial equilibrium model across 20 developing countries.

For each spatial unit, $\triangle ln\, MA_i = ln\, MA_{i,2010} - ln\, MA_{i,2000}$ is calculated using the definition of market access in equilibrium condition (22). For the district-level wage, $w_{n,t}$, I use average expenditure per capita data by district for 2000 and 2010.[25][26] Combined with data as described above on $d_{ni,t}$, $d_{xi,t}$ and E_t and a central estimate from the literature of $\sigma = 7$ (see Chapter 4), this allows me to compute $\triangle ln\, MA_i$.

There are several challenges to direct empirical estimation of the log-linear relationship between changes in wages and changes in market access from equation (28). The first of these is that the productivity term $\triangle ln\, A_i$ is not observed. Subsuming this unobservable term into an error term faces the challenge that changes in locations' productivities may be correlated with changes in transport infrastructure and hence with $\triangle ln\, MA_i$ (any time-invariant productivity differences are removed by first differencing). This concern may be somewhat alleviated by adding a vector X_i of district-level controls for observable variables and regional fixed effects δ_r for each of Vietnam's eight socio-economic regions, yielding the following estimating equation:

$$\triangle ln\, w_i = \beta \triangle ln\, MA_i + \gamma X_i + \delta_r + \varepsilon_i \tag{29}$$

where standard errors are clustered at the level of Vietnam's 63 provinces. This estimating equation remains, however, subject to two key endogeneity concerns. Firstly, the allocation of transport improvements may be endogenous to district characteristics that are unobservable or on which data are not available. Secondly, changes in w_i may be correlated with changes in w_n or L_n in other spatial units, which would introduce a correlation between $\triangle ln\, MA_i$ and $\triangle ln\, w_i$ even in the absence of transport improvements. To

[25]For 5% of districts, expenditure per capita data was not available in 2000. For these districts, I used an imputed value calculated by scaling down 2010 expenditure per capita by the average percentage change in expenditure per capita from 2000 to 2010 across all districts for which data in both years is available.

[26]Results using formal sector wage from the VEC rather than expenditure per capita are also available upon request. These data are much noisier, so the first stage regression coefficients have the expected sign but lower F-statistics.

address these concerns, I instrument for each district's change in market access with its proximity to the Ho Chi Minh Trail, as outlined in Section 2.4, conditional on the same set of controls.

The first stage results, shown in Table 6, suggest that log proximity to the trail is a strong instrument for the change in a district's market access. The second stage IV estimates in Table 7 suggest that, consistent with the model, improvements in market access increase local wages, with a 1% increase in market access associated with a 0.595% increase in expenditure per capita. The estimated effect size is comparable to other estimates in the literature.[27] While both coefficients are positive and significant, the IV estimates are again larger than the OLS estimates, in line with declining regions having been favoured with greater improvements in market access.

The significant positive relationship in the model-derived regression specification is consistent with the equilibrium condition implied by the model's production structure, increasing confidence that the structural model provides a sensible basis for modelling the general equilibrium effects of transport infrastructure improvements in this context.[28]

3.8.2 Structural simulation of reduced form results

In a further test of the model, I use the model structure to simulate the reduced form effects of road upgrades predicted by the model. Comparing these predictions to the realised reduced form results in Table 7 then provides a quantitative test of the model.

[27] For instance, Donaldson and Hornbeck (2016) find that a 1% increase in market access due to the 19th century expansion of American railroads led to an increase of 0.51% in land values and Alder (2017) finds that a 1% increase in market access resulting from Indian highway expansion was associated with a 0.6-0.7% increase in light intensity and a 0.2-0.3% increase in real income.

[28] The regression specification may also be used to inform calibration of one of the model's parameters, the elasticity of substitution between goods σ, since the equilibrium condition in first differences in equation (28) implies that the coefficient on $\triangle ln\, MA_i$ should be equal to $\frac{1}{\sigma}$. The point estimate in the preferred specification implies a slightly lower σ than the calibrated value of 7 used to compute $\triangle ln\, MA_i$. In the structural estimation I use a central estimate of $\sigma = 7$ from the literature, but consider the robustness of the results to using a range of values for σ.

In order to simulate the reduced form effects of road upgrades predicted by the model, I simulate the change in market access and expenditure per capita implied by removal of the realised road upgrades made between 2000 and 2010. I then use these values for $\triangle ln\, MA_i$ and $\triangle ln\, w_i$ as inputs into the OLS regression specified in equation 29.

The results of this exercise are shown in Panel A of Table 8. These results suggest that a 1% increase in market access is associated with a 0.143% increase in expenditure per capita. This estimate is of a comparable order of magnitude to, but somewhat smaller than, the 0.595% increase in expenditure per capita obtained in the reduced form estimates in Table 7. This suggests that the baseline model is if anything too conservative in predicting the impacts of road investments on local economic activity.

The discrepancy between the reduced form estimates and the model-predicted estimates may in part be driven by the fact that the gravity equation 28 is static, so that the model-predicted estimates capture only the contemporaneous impact of road upgrades on expenditure per capita. In contrast, the reduced form estimates in Table 7 result from a long difference over ten years and therefore include the effects of, for instance, endogenous migration responses and correlated investments. Given this, it may be intuitive that the simulated estimates are smaller than those obtained in the reduced form, for example if other types of investments follow roads, increasing productivity A_i over time in areas treated with roads. To investigate this possibility, I re-simulate the model-predicted results assuming that all changes in productivity are due to road upgrades, by using A_i values calibrated from 2000 data.

The results, shown in Panel B of Table 8, suggest that in this case a 1% increase in market access is associated with a 0.792% increase in expenditure per capita.[29] It is intuitive that this result is larger than the estimate

[29]In contrast to the Panel A estimate, the results in Panel B include a standard error and an R^2 value below one. This results from the fact that, with time-varying district productivities, change in log expenditure per capita is no longer a deterministic function of change in log market access in the gravity equation 28.

assuming constant productivities over time, since this captures both the direct effect of market access on local economic activity and the indirect effect that arises via induced increases in productivity. Quantitatively, the reduced form estimate of a 0.595% increase from Table 7 falls between the model-predicted estimates in the two scenarios: the first under the conservative assumption (used in the baseline simulations) that productivities are constant over time and the second under a likely exaggerated assumption that all changes in productivity are accountable to road upgrades. As such, the structural model performs well in a quantitative test of its predictions using the reduced form evidence.

4 Chapter 4: Solving the model

The key question that the structural analysis aims to answer is whether infrastructure investments should favour coastal regions. The model is used to answer this question in my empirical setting by estimating the welfare gains achieved by the realised road upgrades and simulating the counterfactual welfare gains that would have been achieved by alternative allocations of road upgrades concentrated further inland.

This chapter outlines how the model is used to conduct these estimations. Recall that, given data on the distribution of economic activity in an initial period; on the evolution of regional land areas and trade costs across periods; and values for the model's structural parameters, the model can be solved for each location's equilibrium path of wages and employment and the net present value of welfare. This suggests a solution method comprised of the following steps:

1. Choose values for the model's structural parameters.

2. Solve the static production problem in 2010 to obtain relative productivities and market access by district in the initial period.

3. Set assumptions about how sea level rise will alter land areas and trading costs in regions that become inundated in the future.

4. Simulate the model forward at 5-yearly intervals from 2010 to solve for the sequential equilibrium path of $\{L_{n,t}, m_{ni,t}, w_{n,t}, MA_{n,t}\}_{t=0}^{\infty}$ in each location.

5. Re-simulate the model in counterfactual scenarios with alternative distributions of road investments and compare welfare gains relative to the status quo.

Step 1: Choose values for the model's structural parameters

I assume parameter values based on the existing empirical literature and, where possible, data available for Vietnam.

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 $\alpha = 0.85$.

The second parameter for which a value is needed is the elasticity of substitution between goods, σ. A large literature estimates the elasticity of substitution between domestic and imported goods, with estimates generally falling in the range 1-5 (see e.g. Mc Daniel and Balistreri (2003) for a review) but some as high as 10 (e.g. Anderson and Van Wincoop (2004)). Estimates of the elasticity of substitution between products produced in different locations in the same country are often higher and generally lie in the range 4 (e.g. Ossa (2015)) to 9 (e.g. Allen and Arkolakis (2014)). I use a central estimate of 7 for baseline calibrations.

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 et al. (2017) in China[30]). I take 3 as my baseline value for $\frac{1}{\nu}$.

[30]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 et al. (2017) 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

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

Step 2: Calibrate productivities and market access by district in 2010

With the estimates from the previous subsection in hand, I use equilibrium conditions (21) and (22) to obtain the relative productivities and market access values in each district that are consistent with the observed data being an equilibrium outcome of the model in an initial period. The first year for which data is available on all variables needed to calibrate the model at a sufficiently fine geographical resolution is 2010, which is therefore chosen as period $t = 0$. Since data on inter-district migration flows are available for the period 2005-2010, the model is simulated at five-yearly intervals.

The calibration is achieved in two steps. First, observed data on $L_{i,2010}$, $w_{i,2010}$, $d_{ni,2010}$, $d_{xi,2010}$ and E_{2010} in 2010 are used to solve equilibrium condition (22) for market access $MA_{n,2010}$ in each location. Using the calibrated values for $MA_{n,2010}$ and the observed data, equilibrium condition (21) can

output under the preferences interpretation. Other papers obtain estimates for the Fréchet shape parameter governing the heterogeneity of preferences for pairs of residence and workplace locations (e.g. Ahlfeldt et al. (2015) estimate a value of 6.83 for this parameter in Germany, Monte et al. (2018) a value of 4.3 in the USA).

then be used to obtain relative productivities in each location, $\left(\frac{1}{F}\right)^{\frac{1}{\sigma-1}} A_{i,2010}$.

The results of this calibration exercise in 2010 using the baseline parameter values are shown in Figure 7. Reassuringly, the spatial distribution of the calibrated market access and productivity values appears sensible. Market access values are highest for areas with dense road and waterway access, predominantly in the delta regions and along the eastern sea coast. Regions of high calibrated productivities coincide with Vietnam's 'Key Economic Zones' in the southeast, Hanoi-Haiphong corridor and central coast, which are recognised as the country's economic engines with above average growth and investment.

To conduct a more rigorous out-of-sample test of how well the calibrated district productivities correlate with other data on common measures of productivity, I use firm-level data from the VEC to estimate the average total factor productivity (TFP) of formal sector firms in each district. This data 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 labour 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 labour, $Y_i = (TFP)_i L_i$. The estimates are strongly positively correlated with the calibrated productivity values by spatial unit, as shown in Table 9.[31]

Step 3: Set assumptions about future inundation

Future sea level rise will alter the economic geography of Vietnam and hence influence the returns to road investments made today. In the model, I incorporate two effects of inundation on the economy's fundamentals that affect

[31]Productivity values calibrated using the district mean wage (excluding 1% outliers) from the 2010 Vietnam Enterprise Census are also positively correlated with these TFP estimates.

the solution for the sequential competitive equilibrium. First, inundated areas will see a gradual decline in their available land area $H_{n,t}$. Second, inundated areas will experience increases in their trade cost matrices $d_{ni,t}$ and $d_{xi,t}$ as inundated roads become more costly to traverse. To simulate the model forward, I therefore require assumptions on the extent to which each of these variables will be influenced by sea level rise in each period.

There is considerable variation in global sea level rise projections. While more extreme estimates project rises up to 5 metres over the next century (Dasgupta et al. (2009)), the majority of recent estimates lie in the range 0.2 to 2 metres by 2100 (Melillo et al. (2014)), with emerging data suggesting that scenarios at the higher end of this range are more likely.[32] In the baseline estimates, I use a central scenario of a gradual rise reaching 1 metre by 2110, which represents a best estimate of sea level rise over this period based on current projections as summarised in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (Qin et al. (2014)).[33]

I simulate gradual inundation of land below 1 metre elevation over 100 years as follows. I first calculate the proportion of each district's land area below 1 metre and reduce its available land area by this amount in equal increments each period from 2010 to 2110. I then assume that the per-kilometre cost of traversing a stretch of inundated road is double the per-kilometre cost of traversing the most costly road type in 2010, and incrementally increase travel costs on all stretches of road below 1 metre such that they are entirely inundated by 2110.

In order to test how far the simulation results are driven by future inundation, I also run all simulations in a scenario that assumes no future inundation, such that all locational fundamentals including land area and bilateral trade costs are held constant at their 2010 values.

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

[33] 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.

Step 4: Solve for the sequential competitive equilibrium

The next step in the estimation is to simulate the model forward to solve for the equilibrium path of the endogenous variables. Unlike equilibrium conditions (21) and (22) used for the calibrations in Step 2, equilibrium conditions (23) to (25) contain terms in both the current and next period's variables. Furthermore, residential amenities $B_{n,t}$ are unobserved even in the initial period, as are the time-invariant migration costs μ_{in}. Caliendo et al. (2018) develop a convenient method to solve for the path of $\{L_{n,t}, m_{ni,t}, w_{n,t}, MA_{n,t}\}_{t=0}^{\infty}$ even in the presence of these challenges using the equilibrium conditions expressed in relative time differences.

This method takes as given the set of initial conditions $L_{n,0}$, $m_{in,-1}$ and $w_{n,0}$, and an assumed path for the values of the model's fundamentals $\{H_{n,t}\}_{t=0}^{T}$, $\left\{\left(\frac{1}{F}\right)^{\frac{1}{\sigma-1}} A_{n,t}\right\}_{t=0}^{T}$, $\{E_t\}_{t=0}^{T}$, $\{d_{ni,t}\}_{t=0}^{T}$ and $\{d_{xn,t}\}_{t=0}^{T}$ over time. Given data on migration shares $m_{in,t}$, equilibrium condition (24) cannot be solved for a unique value of $V_{i,t+1}$ without data on migration costs μ_{in} and local amenities $B_{n,t}$. By expressing the dynamic equilibrium conditions in time differences, however, the time-invariant migration cost and any time-invariant component of local amenities cancel, such that the sequential equilibrium of the model can be solved for without estimating these terms.

The solution method requires 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 Chapter 6.

Using the assumed future stationarity and the initial conditions, an iterative solution algorithm is used to propagate backwards to find the equilibrium path. Intuitively, the algorithm is based on the fact that each worker makes the optimal migration decision each period taking the distribution of economic activity as given and that, in equilibrium, the path of the endogenous population and wage in each district must coincide with what the workers expect. The relevant equilibrium conditions expressed in relative

time differences are derived at Appendix C and summarised here, where $Y_{n,t+1} = [exp\,(V_{n,t+1} - V_{n,t})]^{\frac{1}{\nu}}$:

1. Expected lifetime utilities:

$$Y_{n,t+1} = \left[\frac{\left(\frac{w_{n,t+1}}{w_{n,t}}\right)^{\alpha}}{\left(\frac{P_{n,t+1}}{P_{n,t}}\right)^{\alpha}\left(\frac{L_{n,t+1}/L_{n,t}}{H_{n,t+1}/H_{n,t}}\right)^{1-\alpha}}\right]^{\frac{1}{\nu}} \times \sum_{k\in N} m_{kn,t}\,(Y_{k,t+2})^{\beta}\,exp\left[\frac{1}{\nu}\,(B_{k,t+1} - B_{k,t})\right] \tag{30}$$

2. Migration shares:

$$\frac{m_{in,t+1}}{m_{in,t}} = \frac{(Y_{i,t+2})^{\beta}(exp[B_{i,t+1}-B_{i,t}])^{\frac{1}{\nu}}}{\sum_{k\in N} m_{kn,t}\left(Y_{k,t+2}\right)^{\beta}\left(exp\left[B_{k,t+1}-B_{k,t}\right]\right)^{\frac{1}{\nu}}} \tag{31}$$

The central estimates assume that local amenities are exogenous and time-invariant, $B_{n,t} = B_n$, so that these equations reduce to:

1. Expected lifetime utilities:

$$Y_{n,t+1} = \left[\frac{\left(\frac{w_{n,t+1}}{w_{n,t}}\right)^{\alpha}}{\left(\frac{P_{n,t+1}}{P_{n,t}}\right)^{\alpha}\left(\frac{L_{n,t+1}/L_{n,t}}{H_{n,t+1}/H_{n,t}}\right)^{1-\alpha}}\right]^{\frac{1}{\nu}} \sum_{k\in N} m_{kn,t}\,(Y_{k,t+2})^{\beta} \tag{32}$$

2. Migration shares:

$$\frac{m_{in,t+1}}{m_{in,t}} = \frac{(Y_{i,t+2})^{\beta}}{\sum_{k\in N} m_{kn,t}\left(Y_{k,t+2}\right)^{\beta}} \tag{33}$$

In the central case, I assume that agents are perfectly foresighted about the future effects of climate change. In this case, the solution to the sequential competitive equilibrium can be found by solving equilibrium conditions (21), (22) and (25), together with the equilibrium conditions in relative time differences (30) and (31). In Chapter 6, I consider the robustness of the results to incorporating myopic agents for whom sea level rise arrives as an unanticipated shock. The solution algorithm in this case is described at Appendix

B.

Step 5: Re-simulate the model in counterfactual scenarios

The simulations in Step 4 solve for the sequential competitive equilibrium taking as given the distribution of economic activity in 2010 and trade costs across periods. Both of these are influenced by the allocation of road upgrade investments made between 2000 and 2010. In order to estimate the counterfactual impacts of alternative allocations of road upgrades over this period (including the case in which no upgrades had been made), the model is re-simulated using trade cost matrices d_{ni} and d_{xi} that reflect these alternative allocations.

Equation (26) can be used to derive the change in welfare induced by these changes in the economy's fundamentals. Denoting by $\widehat{x}$ the value of a variable x under an alternative scenario for the economy's fundamentals, welfare in location n at time t with and without the change in fundamentals are given by, respectively:

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

and:

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

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

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

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

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

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

$$\begin{aligned}\triangle Welfare_{t} &= \sum_{n\in N}\frac{L_{n,0}}{\sum_{i\in N}L_{i,0}}\times \\ &\left\{(1-\beta)\sum_{s=t}^{\infty}\beta^{s-1}ln\left(\frac{\left(\frac{\widehat{w_{n,s}}}{w_{n,s}}\right)^{\alpha}\frac{exp\left(\widehat{B_{n,s}}\right)}{exp\left(B_{n,s}\right)}}{\left(\frac{\widehat{P_{n,s}}}{P_{n,s}}\right)^{\alpha}\left(\frac{\widehat{L_{n,s}}/L_{n,s}}{\widehat{H_{n,s}}/H_{n,s}}\right)^{1-\alpha}\left(\frac{\widehat{m_{nn,s}}}{m_{nn,s}}\right)^{\nu}}\right)\right\}\end{aligned} \tag{34}$$

5 Chapter 5: Quantifying the effects of realised road upgrades

In this chapter, I use the model to quantify the dynamic welfare gains from the realised road upgrades made in Vietnam between 2000 and 2010 by simulating the effects of their removal. To isolate the effect of road upgrades alone, seaport proliferation and capacity upgrades between 2000 and 2010 are incorporated in all counterfactuals, as are changes in mobilisation costs, direct transport costs per km and travel speeds on each mode.

In the central estimates with gradual inundation of the sub-1m low elevation coastal zone over the next century, the results show that the net present value of aggregate welfare was 1.74% higher as a result of the realised road upgrades made between 2000 and 2010 than it would have been if no upgrades had been made. This estimate is comparable to the estimated effects of transportation infrastructure investments in other contexts, which generally lie in the range 1-2% (e.g. Allen and Arkolakis (2014), Alder (2017)). Relative to existing estimates in the literature, however, this estimate incorporates dynamic gains from the investments in future periods (which will tend to increase welfare impacts) and the effects of future sea level rise (which will tend to reduce welfare impacts).

In order to distinguish these effects, I re-simulate the model in a scenario with no future inundation. In this case, the net present value of aggregate welfare in 2010 is estimated to be 2.49% higher as a result of the realised road upgrades. It is intuitive that higher gains should accrue to the investments in the absence of sea level rise, since a large share of upgraded roads are lost to inundation, or connect areas that are. This will impose welfare costs relative to a scenario with no inundation since the economy will no longer benefit from the trade cost gains from road upgrades once these are under water, and because there are migration costs associated with future population reallocation out of inundated areas.

These simulations also reveal that the realised road upgrades reinforce

the concentration of populations in the sub-5m low elevation coastal zone relative to the scenario in which no road upgrades had been made, consistent with the motivating evidence that upgrades 'favoured' coastal areas.[34] The changes in district-level populations induced by the road investments by 2110 are shown in the first panel of Figure 8. Consistent with this pattern, welfare gains are also most strongly concentrated in the (predominantly coastal) districts receiving particularly strong concentrations of road upgrades over the period, as shown in the first panel of Figure 9.

[34]The key measure of geographic vulnerability used is the sub-5m LECZ. While sea level rises of this magnitude are unlikely to be observed over at least the next century, this region captures a broader area likely to be affected by more severe storms and associated storm surges, increased severe flooding, saltwater intrusion and depletion of protective mangrove systems as sea levels rise (Nguyen et al. (2007), DiGregorio (2013)). I consider a spatial unit to lie in the sub-5m LECZ if the median value of elevation cells in the spatial unit is 5m or lower.

6 Chapter 6: Policy counterfactuals

In this chapter, I consider whether higher aggregate welfare gains could have been achieved had the same total investment amount been allocated to upgrade different stretches of the road network, especially those that avoid the adverse consequence of encouraging increased concentration of the population in the LECZ. In order to do this, I use the same estimation method outlined in Chapter 4 to quantify the welfare gains in counterfactual scenarios in which road upgrades with approximately the same total cost as the realised upgrades had been allocated elsewhere.[35] For expositional clarity, welfare gains in all scenarios are measured relative to the case in which no upgrades had been made over the period.

6.1 Counterfactual allocation rules

To select the counterfactual networks, I consider objective allocation rules that have been used by transport planners in other countries or as a benchmark against which misallocation has been measured in the literature. These allocations offer the advantage that they are not model-dependent and of having a direct interpretation for policymakers to ensure implementability.[36] Figure 10 presents the 2010 road map and a map of the realised road upgrades made in Vietnam from 2000 to 2010. Figures 11 to 14 present the equivalent maps implied by each of the counterfactual scenarios, described below.

[35] There are minor differences in the construction costs of the counterfactuals due to integer constraints. The results are robust to adjusting for these small differences, for example by comparing return on investment figures rather than percentage welfare gains.

[36] The counterfactuals considered here do not attempt to identify the globally optimal transport network. While a recent literature has sought to identify optimal transport networks in particular classes of static general equilibrium spatial models (e.g. Fajgelbaum and Schaal (2017) and Allen and Arkolakis (2016)), these networks are necessarily model-dependent and not directly interpretable for policymakers. This literature has also focused on static models, in contrast to the dynamic setup considered here.

Counterfactual scenario based on connecting major administrative divisions

The first counterfactual simulates a hypothetical allocation of road investments in which upgrades had been geographically allocated based on a simple objective rule of thumb. This aims to capture the effect of a counterfactual allocation of road investments that does not specifically try to avoid the LECZ but - in contrast to the observed allocation of upgrades - does not systematically favour these regions either.

The counterfactual is based on a rule to connect major administrative divisions, which has formed the basis of major road development projects in several countries (e.g. Brazil (Morten and Oliveira (2014)) and China (Alder (2017))). I first use ArcGIS's Network Analyst extension to find the lowest cost route connecting all province centroids along the 2000 road network. I then simulate outcomes in the counterfactual scenario in which all roads along this route had been upgraded to a dual carriageway. The implied road network in 2010, shown in Figure 11, shows a much more even distribution of road upgrades across the country relative to the realised allocation.

Counterfactual scenario maximising market potential

This counterfactual tries to improve, in aggregate welfare terms, upon the previous allocation's simple rule of thumb. To achieve this, road upgrades are allocated following an approach similar to that proposed in Burgess et al. (2015) to maximise the market potential measure in Fujita et al. (2001), a metric used by transport planners in allocating roads.

To construct the counterfactual, I first rank pairs of spatial units according to their 2000 market potential, calculated as the sum of the units' populations divided by the Euclidean distance between them. I then use ArcGIS to find the quickest route between each of these pairs, and allocate one category road upgrades to these bilateral connections in order of the market potential ranking until approximately the same total investment in road upgrades as under the status quo has been allocated. The implied road

network is shown in Figure 12. As is evident from the figure, this scenario implies some concentration of upgrades in the LECZ (in line with its concentration of existing populations, on which the market potential measure is based), but is less strongly concentrated in the LECZ than the status quo allocation.

Counterfactual scenario avoiding 5m low elevation coastal zone

The previous counterfactuals simulate spatial allocations of road investments that are based on the existing distribution of the population. An important motivation for this research is the likelihood that historical population distributions may not be a good guide to patterns of locational advantage in the future, particularly in geographically vulnerable coastal locations. Given this and the place-making role of infrastructure investments, allocations that continue to favour existing population concentrations may help to 'lock in' an inefficient trajectory over time. To investigate this possibility, the final counterfactuals consider hypothetical allocations of road investments that try to avoid the LECZ altogether. Such a strategy may be expected to encourage a shift of economic activity and population towards higher elevations and hence confer longer-run benefits as climate changes take effect.

To construct this counterfactual network, I rank all pairs of spatial units outside the sub-5m LECZ according to their 2000 market potential, use ArcGIS to find the quickest route between each of these pairs that avoids the sub-5m LECZ and allocate one category road upgrades to these bilateral connections in order of the market potential ranking until approximately the same total investment in road upgrades as under the status quo has been allocated. The implied allocation of road upgrades, shown in Figure 13, is therefore much more strongly concentrated at higher elevations than the realised allocation.

Counterfactual scenario avoiding 1m low elevation coastal zone

The final counterfactual is intermediate between the latter two counter-

factuals. This reflects the likelihood that near-term welfare gains from some infrastructure investment in coastal and delta regions are likely to be important even if there are dynamic gains from reallocating investments away from the most hazardous areas in the future. As such, avoiding the sub-5m LECZ altogether is likely too extreme a scenario to maximise the net present value of discounted future welfare from the road investments. I therefore consider a scenario that allows for some investment in the sub-5m LECZ while avoiding construction only in the most hazardous areas below 1 metre.

To construct this counterfactual network, I rank all pairs of spatial units according to their 2000 market potential except for those districts whose median elevation is below 1 metre. I then use ArcGIS to find the quickest route between each of these pairs and allocate one category road upgrades to these bilateral connections in order of the market potential ranking until approximately the same total investment in road upgrades as under the status quo has been allocated. The distribution of road upgrades in this case, shown in Figure 14, is intermediate between the unconstrained allocation maximising market potential and the allocation maximising market potential outside the sub-5m LECZ.

6.2 Results of counterfactual simulations

The results of the counterfactual simulations in the central scenario with a gradual 1m rise in the sea level are shown in Figure 15. Although the status quo allocation outperforms the simple rule of thumb, the other counterfactuals all achieve significantly higher aggregate welfare gains. The allocation that performs best is the counterfactual avoiding the sub-1m LECZ, which achieves welfare gains 72% higher than that achieved by the realised upgrades. The market potential maximising allocation also achieves significantly higher gains (64%) relative to the status quo, but does not perform as well as the foresighted allocation avoiding the 1m LECZ as a relatively large share of upgraded roads are still lost to inundation in this case. The allocation maximising market potential outside the sub-5m LECZ achieves

smaller relative welfare gains of 29% versus the status quo as this allocation foregoes the gains to investing in districts at intermediate elevations.

It is in some sense unsurprising that the realised allocation of road upgrades was not optimal: very little is known about optimal spatial policy (Ossa (2015)) and the literature is replete with examples of potential inefficiencies that may distort choices away from any optimum even if it were known (e.g. Burgess et al. (2015), Glaeser (2010), Do et al. (2017)). Of particular interest for this analysis is the question of how far the inefficiency in the realised allocation is driven by the future inundation of coastal areas, which received a high share of upgrades under the realised allocation. There are 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)).

To disentangle the effect of future inundation from other potential drivers of misallocation, I re-run each counterfactual simulation in the scenario with no future sea level rise. The results are shown in Figure 16. The overall finding that all counterfactuals except the simple rule of thumb perform at least as well as the status quo is robust to excluding the effects of future sea level rise. In this scenario, the counterfactuals maximising market potential and maximising market potential outside the 1m LECZ induce welfare gains 55% and 48% higher than the status quo respectively, while the counterfactual avoiding the sub-5m LECZ achieves almost the same gains. The highest returns are achieved by the unconstrained counterfactual maximising market potential, an intuitive result since the constraints to avoid low elevation coastal zones are irrelevant in the absence of sea level rise. All of the counterfactuals induce long-term population declines in the sub-5m LECZ relative to the status quo, as shown in Figure 8. The change in district-level welfare brought about by each counterfactual, shown in Figure 9, again reveals

the strongest welfare gains in districts receiving high concentrations of road upgrades.

Taken together, the two sets of simulation results suggest that there is over-investment in coastal areas both with and without accounting for the effects of future sea level rise. This 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)). It is also in line with the related literature on policy myopia (Nordhaus (1975), Rogoff (1990), Rodrik (1996)), which suggests that, where policymakers face short electoral time horizons, 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.

The dynamic simulations also reveal the significant shift that future sea level rise induces in the relative welfare gains implied by each road investment allocation. These results are summarised in Figure 17 and provide a stark demonstration of how projected environmental changes may alter the relative dynamic benefits of different allocations of infrastructure investments today. The realised road investments are rendered significantly less efficient relative to the counterfactuals once we take into consideration future inundation, since the largest share of upgraded roads are concentrated in inundated areas. Incorporating the effects of future sea level rise also changes the relative performance of the counterfactuals: while unconstrained maximisation of market potential yields the higest gains in the absence of sea level rise, with inundation it is the foresighted allocation avoiding regions below 1 metre that achieves the highest welfare gains. As such, consideration of future environmental change is central to assessing the returns to investments made today and in selecting between different allocation rules.

The timescales over which climate changes are projected to materialise, the rapid pace of change in the Vietnamese economy and uncertainty around future adaptation measures make it challenging to forecast accurately the impacts of future sea level rises. Nevertheless, the simulations demonstrate

that future climate changes are likely to alter significantly the benefits afforded by infrastructure investments made today. Evidence from the path dependence literature suggests that new investments tend to follow old ones, magnifying these effects over time. To the extent that path dependence encourages further investments to follow these infrastructure allocations, the figures above may be conservative estimates of the dynamic welfare gains that could be achieved by foresighted investment allocations today.

6.3 Alternative explanations

The results of counterfactual structural analyses will be influenced by 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)). To the extent that road investments may be expected to induce local increases in productivity or amenity values, the results in the previous sub-section may be conservative estimates of the potential welfare gains from the counterfactual allocations of road upgrades. However, there are alternative assumptions about the model's parameters that may increase the returns to favouring coasts. This section considers how far these alternative explanations may help to rationalise the observed allocation of road upgrades.

6.3.1 Changes in coastal amenity values

While hazard-prone, coastal areas also confer amenities such as sea views and recreation opportunities. This is reflected in a 'coastal premium' for residential housing prices which has been estimated in developed country contexts (Benson et al. (1998), Fraser and Spencer (1998) Conroy and Milosch (2011)). While the baseline estimates account for *fixed* differences in amenity values across locations, it is possible that an increase in the amenity value attached to coastal proximity as development proceeds may help to rationalise the observed road allocations.

In order to test this, I re-simulate the model making the following assumptions about the trajectory of local amenities over time. The studies in developed countries cited above estimate a coastal premium in the range of 25-100%. The premium is highly localised and disappears approximately 10km inland from the coast (Conroy and Milosch (2011)). I therefore assume that all districts with some land area within 10km of Vietnam's sea coast experience an increase in local amenities over time, while these remain constant in other districts. 193 of the 541 districts used in the analysis contain some land area within 10km of Vietnam's sea coast, and 44% of the land area of these districts is within 10km of the coast. I make the conservative assumption 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 (this reflects a central estimate of the coastal premium of 50% applied to 44% of their land area), increasing in equal increments each period in the interim.

The results incorporating this assumption are shown in Figure 18 and are consistent with the patterns in the central estimates. As such, a change in the coastal amenity premium as Vietnam's development proceeds does not appear to rationalise the coastal favouritism observed in the realised road upgrades.

6.3.2 Secular change in productivities

The assumption in the baseline simulations that all variables other than the inundated land area and roads will remain constant over the next century is unlikely to be realistic, particularly as regards regional productivities. While it is clearly challenging to predict how these will evolve 100 years hence, we may expect major recent trends that have driven changes in regional advantage (such as structural change or increasing tourism) to continue into the future. To test this, I re-simulate the model assuming that the trends in relative productivities across districts that were observed over 2000-2010 continue over the subsequent decade. I assume that the same rate of di-

vergence in regional productivities as witnessed over 2000-2010 applies from 2010-2020 and productivities are linearly interpolated for the five-yearly interval in between. The results in this case are shown in Figure 19. Again the market potential maximising allocation offers the highest returns if the effects of future sea level rise are ignored, but the allocation maximising market potential outside the 1m LECZ affords the highest returns once the effects of future sea level rise are included in the analysis.

6.3.3 Secular change in international trade

Another quantity which we might expect to undergo secular change over the simulation period is international exports. If international trade continues to grow in line with the recent historical trajectory, this might be expected to favour coastal regions with easy access to international ports. I therefore simulate the model assuming that international exports continue to grow across each period for the next 50 years in line with the growth rate in international exports witnessed from 2010-2015.

The results in this case are shown in Figure 20. In this scenario the relative welfare gains of the counterfactuals relative to the realised investments are somewhat attenuated. However, it remains the case that significantly higher gains are achieved by the counterfactual maximising market potential in the scenario without future sea level rise (welfare gains 42% higher than the status quo) and the counterfactual maximising market potential outside the 1m LECZ in the scenario with future sea level rise (welfare gains 30% higher than the status quo).

6.4 Robustness checks

The results in the previous sub-section suggest that alternative assumptions about the trajectory of locational fundamentals and agents' preferences cannot overturn the key findings that there is over-investment in coastal areas (with or without sea level rise) and that under central sea level rise scenarios

the highest gains are achieved by an allocation avoiding the most vulnerable regions. This section tests the robustness of the results to varying assumptions about agents' information as well as values of the model's structural parameters and data sources.

6.4.1 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. In this section I consider the robustness of the results to instead assuming that agents are myopic about the effects of sea level rise in the future.

As described in Appendix B, the solution algorithm in the case with myopic agents requires that an additional sequential equilibrium for all future time periods must be computed each time a new unexpected shock arrives. As a result, it is not computationally feasible to simulate a scenario under which gradual sea level rise arrives as an unexpected shock every (five-year) period. Arguably, nor would this in any case be the most realistic way to model myopic agents' expectations about future sea level rise. Instead, I assume that agents expect that sea level rise will occur in line with climate projections 50 years into the future but that levels will stabilise thereafter. This could reflect, for instance, an expectation of future mitigation measures or scepticism regarding longer-range climate projections. As such, continuing sea level rise arrives as an unanticipated shock after 50 years.

Figure 21 presents the results in the case where agents are myopic about future sea level rises. As was the case when sea level rise was anticipated, the realized road investments experience the sharpest decline in returns, while the foresighted allocations avoiding the sub-5m LECZ and sub-1m LECZ see the most modest decline. The highest returns are again achieved by the counterfactual allocation avoiding the sub-1m LECZ, which achieves welfare gains 67% higher than the status quo.

6.4.2 Depreciation of road investments

The central simulations consider the effects of the major ten-year road upgrade programme 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. In reality, the Government may alter the spatial distribution of road maintenance and upgrading in future periods. It is of course challenging to predict how the Government may distribute future road investments across space in all future periods. To the extent that it is cheaper to maintain existing roads than to build new ones, and that the location of existing roads is likely to be self-reinforcing as people and firms agglomerate nearby, the central assumption that the Government maintains existing roads equally may be a sensible approximation. However, I also test the robustness of the results to assuming that there is differential depreciation of the road upgrades made from 2000-2010, such that only road upgrades made over this period depreciate fully within 30 years.

The results in this case are shown in Figure 22. The discrepancy between the gains from the unconstrained and constrained market potential maximising allocations in the central scenario incorporating sea level rise is somewhat attenuated. This reflects the reduced importance of the constraint for upgrades to avoid inundation-prone areas in a scenario in which the upgrades will have depreciated by the time the worst of the inundation materialises. Nonetheless, these results again suggest that the counterfactual maximising market potential outside the 1m LECZ achieves the highest gains in the scenario incorporating future sea level rise (welfare gains 62% higher than the status quo), and the unconstrained market potential maximising alloaction achieves the highest gains in the scenario without future sea level rise (welfare gains 53% higher than the status quo).

6.4.3 Alternative discount factor

As discussed in Chapter 4, the annual discount factor of 0.96 used in the central estimates is used commonly in the macroeconomics literature, but is conservative in this context. Figure 23 presents results using an annual discount factor of 0.986 in line with more recent studies and the climate change literature. The results in this case display the same pattern as in the central estimates but with more pronounced magnitudes. In this case, the welfare gains implied by the counterfactual allocation avoiding the sub-1m LECZ exceed those of the status quo by 96%, while the relative gains implied by the counterfactuals maximising market potential and maximising market potential outside the sub-5m LECZ are 72% and 52% respectively.

6.4.4 Using formal sector wage data

As outlined in Chapter 2, two sources of wage data are available for each spatial unit used in the analysis. The main analysis uses expenditure per capita data estimated at the district level using small area estimation based on data from the VHLSS and population census. Data is also available on formal-sector wage at the district level from the VEC. Given the strong correlation between these two sources of wage data, very similar results are obtained using the VEC wage data, as shown in Figure 24.

6.4.5 Timing of stationary equilibrium

As discussed in Chapter 4, the model solution requires that the economy approaches a stationary equilbirium in which aggregate variables do not change over time. The central estimates assume that the economy reaches a stationary equilibrium in 250 years. To test how this assumption influences the results, the model is re-simulated assuming that the stationary equilibrium is instead reached in 200 and 400 years. The results are indistinguishable from the central estimates in both cases.

7 Chapter 7: Conclusions

Transport infrastructure investments attract huge levels of investment globally and this trend is set to intensify as developing countries invest in expansion and upgrading of their infrastructure networks. The burgeoning literature on the role of transport infrastructure in determining the spatial pattern of development finds sizeable effects on the distribution of economic activity and welfare. It is therefore important to consider the placement of these investments carefully. This thesis 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 microdata in an illustrative country, allows me to quantify the significant gains that will be unrealised if infrastructure investments are not moved away from areas vulnerable to environmental change. I look at the full picture of gains and losses by juxtaposing reduced form estimates of the local effects of investments with structural estimates that capture general equilibrium effects.

I find that there are unrealised gains from moving place-making investments further inland even without consideration of environmental change. Reallocating investments away from coastal regions today ensures that they garner much larger returns than allocations that follow where populations *currently* are. Compounding this, the global climate is now 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)). The results suggest that, in the presence of these changes, the welfare gains from avoiding vulnerable areas are extremely large. This highlights the importance of opening up a literature that connects environmental change to the location of economic production.

The set of issues considered in this thesis are by no means only relevant in developing countries. Indeed all countries with large population concentrations in coastal regions are increasingly cognisant 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 thesis could be applied to a range of contexts where authorities are rethinking the allocation of infrastructure investments across space.

Developing countries require special focus, however, both because these economies are likely less able to afford the resources to protect their coastal populations from future inundation, and given that developing countries will be responsible for the majority of infrastructure investments in the coming decades. It may therefore be even more pressing for infrastructure allocations in these contexts to take into consideration the costs this thesis 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.

References

ADB (2012). Vietnam transport sector assessment, strategy, and road map. Technical report, Asian Development Bank.

Adger, W. N., T. P. Hughes, C. Folke, S. R. Carpenter, and J. Rockström (2005). Social-ecological resilience to coastal disasters. *Science 309*(5737), 1036–1039.

Ahlfeldt, G. M., S. J. Redding, D. M. Sturm, and N. Wolf (2015). The economics of density: Evidence from the Berlin Wall. *Econometrica 83*(6), 2127–2189.

Alder, S. (2017). Chinese roads in India: The effect of transport infrastructure on economic development.

Allen, T. and C. Arkolakis (2014). Trade and the topography of the spatial economy. *Quarterly Journal of Economics 129*(3), 1085–1140.

Allen, T. and C. Arkolakis (2016). The welfare effects of transportation infrastructure improvements.

Allen, T. and D. Donaldson (2018). The geography of path dependence.

Anderson, J. E. and E. Van Wincoop (2004). Trade costs. *Journal of Economic Literature 42*(3), 691–751.

Anh, D. N. (1999). Market reform and internal labor migration in Vietnam. *Asian and Pacific Migration journal 8.3: 381-409*.

Artuç, E., S. Chaudhuri, and J. McLaren (2010). Trade shocks and labor adjustment: A structural empirical approach. *The American Economic Review 100*(3), 1008–1045.

Au, C.-C. and J. V. Henderson (2006a). Are Chinese cities too small? *The Review of Economic Studies 73*(3), 549–576.

Au, C.-C. and J. V. Henderson (2006b). How migration restrictions limit agglomeration and productivity in China. *Journal of Development Economics 80.2: 350-388*.

Banerjee, A., E. Duflo, and N. Qian (2012). On the road: Access to transportation infrastructure and economic growth in China. *NBER Working Paper 17897*.

Baum-Snow, N., V. Henderson, M. A. Turner, Q. Zhang, and L. Brandt (2016). Highways, market access, and urban growth in China. *SERC Discussion Papers 200*.

Benson, E. D., J. L. Hansen, A. L. Schwartz, and G. T. Smersh (1998). Pricing residential amenities: the value of a view. *The Journal of Real Estate Finance and Economics 16*(1), 55–73.

Birkmann, J., M. Garschagen, P. Mucke, A. Schauder, T. Seibert, T. Welle, J. Rhyner, S. Kohler, T. Loster, D. Reinhard, et al. (2014). World risk report 2014.

Blancas, L. C. and M. B. El-Hifnawi (2013). Facilitating trade through competitive, low-carbon transport: The case for Vietnam's inland and coastal waterways. Technical report.

Bleakley, H. and J. Lin (2012). Portage and path dependence. *The Quarterly Journal of Economics 127*(2), 587.

Bryan, G. and M. Morten (2018). The aggregate productivity effects of internal migration: Evidence from Indonesia. *Journal of Political Economy*.

Burby, R. J. (2006). Hurricane Katrina and the paradoxes of government disaster policy: Bringing about wise governmental decisions for hazardous areas. *The Annals of the American Academy of Political and Social Science 604*(1), 171–191.

Burgess, R., R. Jedwab, E. Miguel, A. Morjaria, and G. Padro i Miquel (2015). The value of democracy: Evidence from road building in Kenya. *American Economic Review 105(6)*, 1817–51.

Caliendo, L., M. Dvorkin, F. Parro, et al. (2018). Trade and labor market dynamics: General equilibrium analysis of the China trade shock. *Econometrica*.

Chandra, A. and E. Thompson (2000). Does public infrastructure affect economic activity?: Evidence from the rural interstate highway system. *Regional Science and Urban Economics 30*(4), 457–490.

Chauvin, J. P., E. Glaeser, Y. Ma, and K. Tobio (2017). What is different about urbanization in rich and poor countries? Cities in Brazil, China, India and the United States. *Journal of Urban Economics 98*, 17–49.

CIESIN (2013a). Global roads open access data set, version 1 (groadsv1). Technical report, Center for International Earth Science Information Network, Columbia University & Information Technology Outreach Services, University of Georgia.

CIESIN (2013b). Low elevation coastal zone urban-rural population and land area estimates, version 2. Technical report, Center for International Earth Science Information Network, Columbia University, Palisades, NY: NASA Socioeconomic Data and Applications Center.

Conroy, S. J. and J. L. Milosch (2011). An estimation of the coastal premium for residential housing prices in San Diego County. *The Journal of Real Estate Finance and Economics 42*(2), 211–228.

Crompton, G. (2004). The tortoise and the economy - inland waterway navigation in international economic history. *The Journal of Transport History 25*(2), 1–22.

Dasgupta, S., B. Laplante, C. Meisner, D. Wheeler, and J. Yan (2009). The impact of sea level rise on developing countries: a comparative analysis. *Climatic change 93*(3-4), 379–388.

Davis, M. A. and F. Ortalo-Magné (2011). Household expenditures, wages, rents. *Review of Economic Dynamics 14*(2), 248–261.

Desmet, K., R. E. Kopp, S. A. Kulp, D. K. Nagy, M. Oppenheimer, E. Rossi-Hansberg, and B. H. Strauss (2018). Evaluating the economic cost of coastal flooding. *NBER Working Paper 24918*.

Dhingra, S., H. Huang, G. Ottaviano, J. Paulo Pessoa, T. Sampson, and J. Van Reenen (2017). The costs and benefits of leaving the EU: trade effects. *Economic Policy 32*(92), 651–705.

DiGregorio, M. (2013). Learning from typhoon Mirinae: Urbanization and climate change in Quy Nhon City, Vietnam. *Institute for Social and Environmental Transition. Hanoi, Vietnam: ISET-Vietnam*.

Do, Q.-A., K.-T. Nguyen, and A. N. Tran (2017). One mandarin benefits the whole clan: hometown favoritism in an authoritarian regime. *American Economic Journal: Applied Economics 9*(4), 1–29.

Donaldson, D. (2018). Railroads of the Raj: Estimating the impact of transportation infrastructure. *American Economic Review 108*(4-5), 899–934.

Donaldson, D. and R. Hornbeck (2016). Railroads and American economic growth: A market access approach. *Quarterly Journal of Economics 131*(2), 799–858.

Duranton, G. and M. A. Turner (2012). Urban growth and transportation. *The Review of Economic Studies 79*(4), 1407–1440.

Eaton, J. and S. Kortum (2002). Technology, geography, and trade. *Econometrica 70*(5), 1741–1779.

Faber, B. (2014). Trade integration, market size, and industrialization: evidence from China's national trunk highway system. *The Review of Economic Studies 81*(3), 1046–1070.

Fajgelbaum, P. D. and E. Schaal (2017). Optimal transport networks in spatial equilibrium. *NBER Working Paper 23200*.

Falvey, L. (2010). History of rice in Southeast Asia and Australia. *Rice: Origin, Antiquity and History*, 183–224.

Financial Times (1997). Ho Chi Minh highway plan: Vietnam announces a new link from Hanoi to the far south.

Forbes, D. (1996). Urbanization, migration, and Vietnam's spatial structure. *Sojourn: Journal of Social Issues in Southeast Asia*, 24–51.

Fraser, R. and G. Spencer (1998). The value of an ocean view: an example of hedonic property amenity valuation. *Australian Geographical Studies 36*(1), 94–98.

Fujita, M., P. R. Krugman, and A. Venables (2001). *The spatial economy: Cities, regions, and international trade*. MIT press.

Fujita, M. and T. Mori (1996). The role of ports in the making of major cities: self-agglomeration and hub-effect. *Journal of Development Economics 49*(1), 93–120.

Gaubert, C. (2018). Firm sorting and agglomeration.

GFDRR (2015). Vietnam country profile. Technical report, Global Facility for Disaster Reduction and Recovery.

Glaeser, E. L. (2010). Shrinking Detroit back to greatness. *The New York Times. March 16*.

Glaeser, E. L. and J. D. Gottlieb (2008). The economics of place-making policies. *NBER Working Paper 14373*.

Glewwe, P., M. Gragnolati, and H. Zaman (2002). Who gained from Vietnam's boom in the 1990s? *Economic Development and Cultural Change 50*(4), 773–792.

Gollin, D., M. Kirchberger, and D. Lagakos (2017). In search of a spatial equilibrium in the developing world. *NBER Working Paper 23916*.

GSO (2005). Statistical yearbook of Vietnam 2005. Technical report, General Statistics Office of Vietnam.

GSO (2010a). Result of the Vietnam Household Living Standards Survey 2010. Technical report, General Statistics Office of Vietnam.

GSO (2010b). Statistical yearbook of Vietnam 2010. Technical report, General Statistics Office of Vietnam.

GSO (2011). Migration and urbanization in Vietnam: patterns, trends and differentials. Technical report, General Statistics Office of Vietnam.

Guha-Sapir, D., R. Below, and P. Hoyois (2015). EM-DAT international disaster database. Technical report, Universite Catholique de Louvain, Brussels, Belgium.

Hallegatte, S., C. Green, R. J. Nicholls, and J. Corfee-Morlot (2013). Future flood losses in major coastal cities. *Nature climate change 3*(9), 802.

Helpman, E. (1998). The size of regions. *Topics in Public Economics*, 33–54.

ICEM (2009). Mekong Delta Climate Change Forum Report Volume I. Technical report, International Centre for Environmental Management.

IPUMS (2015). Minnesota Population Center. Integrated Public Use Microdata Series, International: Version 6.4. Minneapolis: University of Minnesota, 2015 and General Statistics Office, Vietnam.

JICA (2000). The study on the national transport development strategy in the Socialist Republic of Vietnam (VITRANSS). Technical report, Japan International Cooperation Agency.

JICA (2010). The comprehensive study on the sustainable development of transport system in Vietnam (VITRANSS-2). Technical report, Japan International Cooperation Agency.

JICA (2014). Data collection survey on transport infrastructure development for regional connectivity in and around South Asia. Technical report, Japan International Cooperation Agency.

Kline, P. M. and E. Moretti (2014). Local economic development, agglomeration economies, and the big push: 100 years of evidence from the Tennessee Valley Authority. *Quarterly Journal of Economics 129*, 275–331.

Kozel, V. (2014). *Well begun but not yet done: Progress and emerging challenges for poverty reduction in Vietnam.* World Bank Publications.

Krugman, P. (1991a). History and industry location: the case of the manufacturing belt. *The American Economic Review*, 80–83.

Krugman, P. (1991b). Increasing returns and economic geography. *Journal of Political Economy XCIX*, 483–499.

Kunreuther, H. (1996). Mitigating disaster losses through insurance. *Journal of Risk and Uncertainty 12*(2-3), 171–187.

Kydland, F. and E. Prescott (2004). Contribution to dynamic macroeconomics: The time consistency of economic policy and the driving forces behind business cycles.

Lanjouw, P., M. Marra, and C. Nguyen Viet (2013). Vietnam's evolving poverty map: patterns and implications for policy. *World Bank Policy Research Working Paper 6355*.

Levinsohn, J. and A. Petrin (2003). Estimating production functions using inputs to control for unobservables. *The Review of Economic Studies 70*(2), 317–341.

Mc Daniel, C. A. and E. J. Balistreri (2003). A review of Armington trade substitution elasticities. *Economie internationale* (2), 301–313.

McCaig, B. and N. Pavcnik (2013). Moving out of agriculture: structural change in Vietnam. *NBER Working Paper 19616*.

McGranahan, G., D. Balk, and B. Anderson (2007). The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. *Environment and urbanization 19*(1), 17–37.

Melillo, J. M., T. Richmond, and G. Yohe (2014). Climate change impacts in the United States. *Third national climate assessment 52*.

Michaels, G. (2008). The effect of trade on the demand for skill: Evidence from the interstate highway system. *The Review of Economics and Statistics 90*(4), 683–701.

Miguel, E. and G. Roland (2011). The long-run impact of bombing Vietnam. *Journal of Development Economics 96*(1), 1–15.

Ministry of Foreign Affairs of Vietnam (2012). Review of Vietnamese migration abroad. Technical report, Consular Department, Ministry of Foreign Affairs of Vietnam.

Mladenovic, G., N. C. Kien, J. Cirilovic, V. Alexeeva, and S. Ishihara (2013). Study of road works contracts and unit costs in Vietnam. Technical report.

Monte, F., S. J. Redding, and E. Rossi-Hansberg (2018). Commuting, migration and local employment elasticities. *American Economic Review*.

Morris, V. (2006). *A History of the Ho Chi Minh Trail: The Road to Freedom*. Orchid Press.

Morten, M. and J. Oliveira (2014). Migration, roads and labor market integration: Evidence from a planned capital city. *NBER Working Paper 22158*.

Nguyen, H. N., K. T. Vu, and X. N. Nguyen (2007). Flooding in Mekong River Delta, Viet Nam. *Human Development Report*.

Nogales, A. (2004). Vietnam transport sector brief.

Nordhaus, W. D. (1975). The political business cycle. *The Review of Economic Studies 42*(2), 169–190.

OECD (2015). ITF transport outlook 2015. Technical report.

Olley, G. S. and A. Pakes (1996). The dynamics of productivity in the telecommunications equipment industry. *Econometrica 64*(6), 1263–1297.

Ossa, R. (2015). A quantitative analysis of subsidy competition in the US. *NBER Working Paper 20975*.

Oxford Economics (2015). Assessing the global transport infrastructure market: Outlook to 2025. PwC.

Patel, J. K., C. Kapadia, and D. B. Owen (1976). Handbook of statistical distributions. Technical report, M. Dekker New York.

Qin, D., G. Plattner, M. Tignor, S. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P. Midgley, et al. (2014). Climate change 2013: The physical science basis. *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (eds TF Stocker et al.)*, 5–14.

Ravallion, M. (1994). *Poverty comparisons*, Volume 56. Taylor & Francis.

Redding, S. and A. J. Venables (2004). Economic geography and international inequality. *Journal of International Economics 62*(1), 53–82.

Redding, S. J. (2016). Goods trade, factor mobility and welfare. *Journal of International Economics 101*, 148–167.

Redding, S. J. and E. A. Rossi-Hansberg (2017). Quantitative spatial economics. *Annual Review of Economics 9*(1).

Redding, S. J. and M. A. Turner (2015). Transportation costs and the spatial organization of economic activity. *Handbook of Urban and Regional Economics Vol 5*.

Rodrik, D. (1996). Understanding economic policy reform. *Journal of Economic Literature 34*(1), 9–41.

Rogoff, K. (1990). Equilibrium political budget cycles. *The American Economic Review 80*, 21–36.

Rosenthal, S. S. and W. C. Strange (2004). Evidence on the nature and sources of agglomeration economies. *Handbook of Regional and Urban Economics 4*, 2119–2171.

Smith, A. (1776). An inquiry into the nature and causes of the wealth of nations: Volume one. London: printed for W. Strahan; and T. Cadell, 1776.

Staiger, D. and J. Stock (1997). Instrumental variables regression with weak instruments. *Econometrica 65*, 557–586.

Starrett, D. (1978). Market allocations of location choice in a model with free mobility. *Journal of Economic Theory 17*(1), 21–37.

Stern, N. H. (2007). *The Economics of Climate Change: The Stern Review*. Cambridge University Press.

Tanzania Ministry of Works (2011). Road geometric design manual. Technical report.

Thao, N. D., H. Takagi, and M. Esteban (2014). Coastal disasters and climate change in Vietnam: Engineering and planning perspectives.

Tombe, T., X. Zhu, et al. (2017). Trade, migration and productivity: A quantitative analysis of China.

Turner, R. K., S. Subak, and W. N. Adger (1996). Pressures, trends, and impacts in coastal zones: interactions between socioeconomic and natural systems. *Environmental Management 20*(2), 159–173.

Vigdor, J. (2008). The economic aftermath of Hurricane Katrina. *The Journal of Economic Perspectives 22*(4), 135–154.

Wang, J. (2013). The economic impact of special economic zones: Evidence from Chinese municipalities. *Journal of Development Economics 101*, 133–147.

Tables and Figures

Figure 2: Economic geography of Vietnam

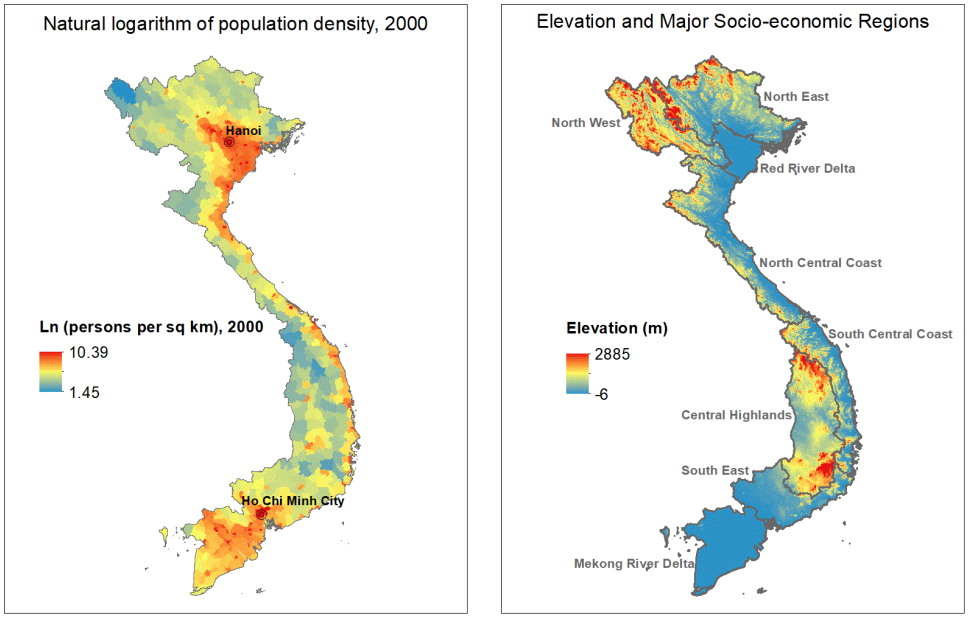
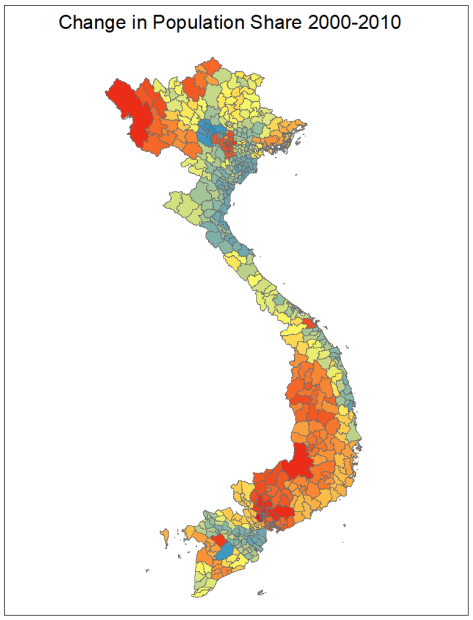


Figure 3: District-level population changes, 2000-2010



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

Figure 4: Natural hazard vulnerability in Vietnam

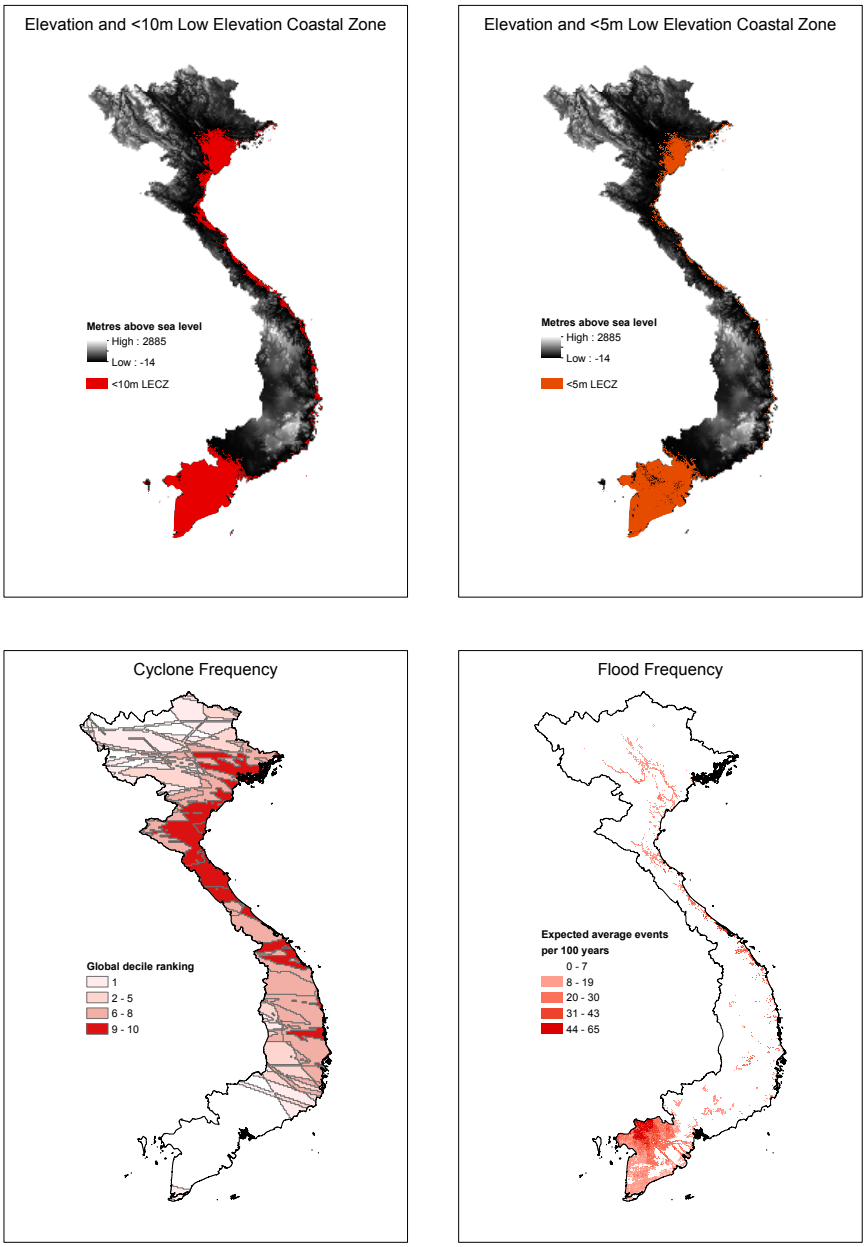


Figure 5: Road maps of Vietnam, 2000 and 2010

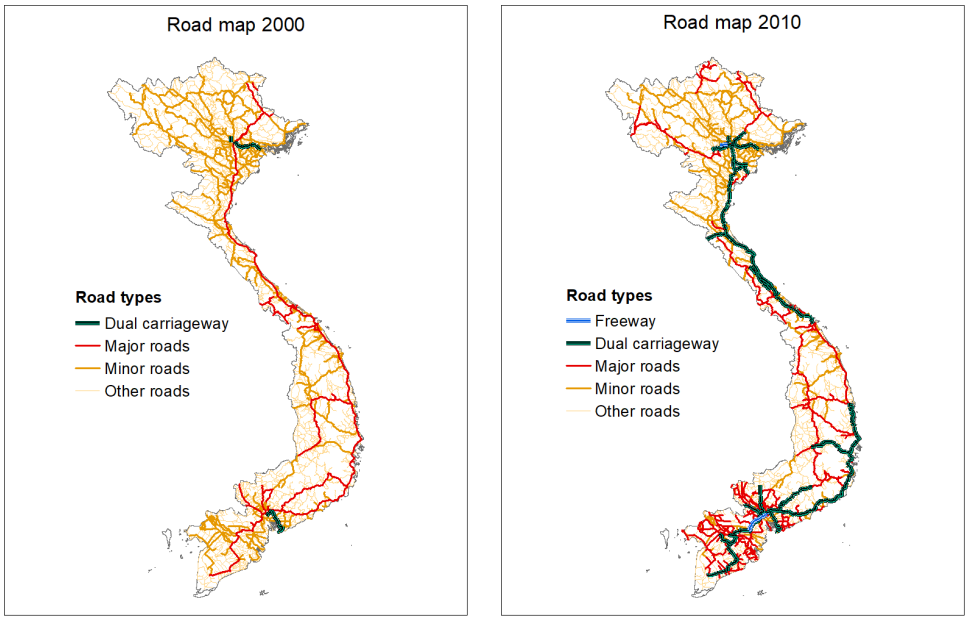


Table 1: Weighted length of road improvements by district, 2000-2010

Weighted length of road improvements by district (km), 2000-2010			
District centroid in 5m LECZ	19.21**	31.43***	20.15**
	(8.313)	(8.340)	(8.514)
District land area		0.0273***	0.0257***
		(0.00470)	(0.00462)
ln (district population 2000)			24.88***
			(5.226)
Observations	541	541	541
R-squared	0.010	0.068	0.106

Standard errors in parentheses. Weighted length of road improvements assigns weight 1 to roads upgraded by 1 category, 2 to roads upgraded by 2 categories, and so on. *** p<0.01, ** p<0.05, * p<0.1.

Figure 6: Route of the Ho Chi Minh Trail, 1969-1973

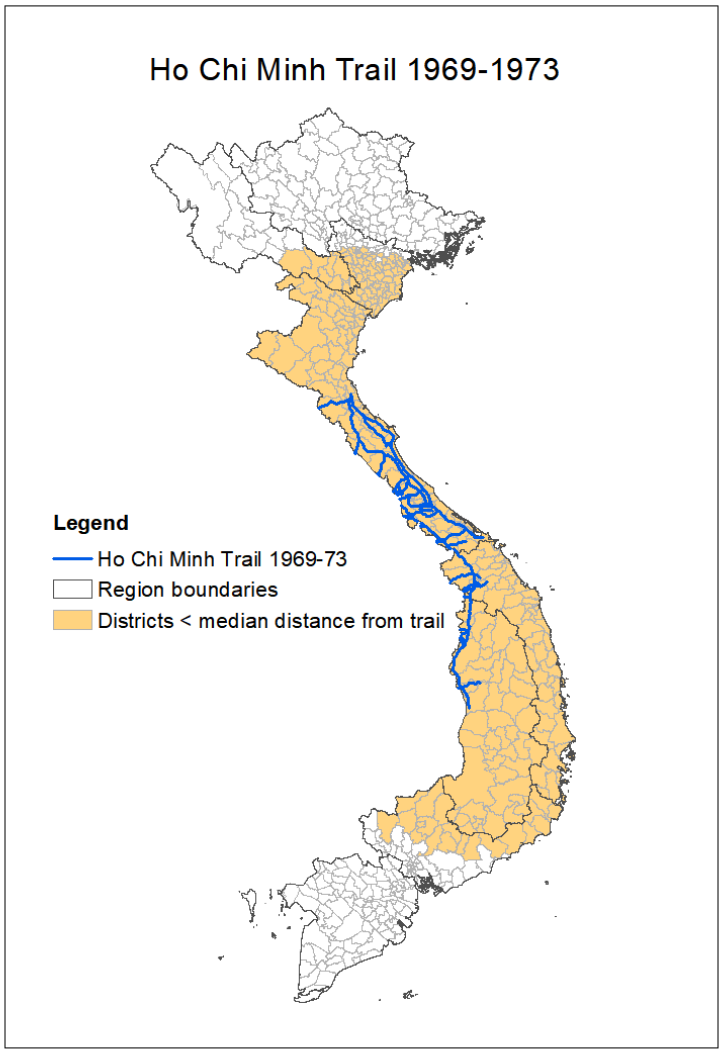


Table 2: Summary statistics of variables used in reduced form regressions

Variable	Mean	Standard deviation
Change in ln expenditure pc 2000-2010	1.002	0.161
Change in poverty rate 2000-10	-0.0812	0.382
Change in ln population 2000-10	0.0981	0.246
Change in ln market access 2000-2010	3.197	0.326
Weighted km upgraded roads	67.14	89.97
ln (proximity to upgraded road)	-8.573	1.812
ln (density upgrades within 50km)	6.612	1.467
Km of HCM Trail	7.351	30.90
ln (proximity to HCM Trail)	-12.02	1.360
Province capital	0.116	0.321
ln (population 2000)	11.67	0.712
Poverty rate 2000	0.410	0.194
Urban share 1999	0.219	0.277
Formal sector share 2000	0.0324	0.0606
Literacy rate 1999	0.879	0.107
ln (weighted km roads 2000)	10.74	0.773
ln (dist to Hanoi or HCMC)	11.67	1.130
ln (dist to coast)	10.38	1.422
ln (land area)	5.787	1.276
Mean elevation (m)	196.4	289.3
Mean slope (%)	5.980	6.177
Average precipitation (cm)	154.6	30.67
Average temperature (Celsius)	24.36	1.831
% land cultivated	13.91	21.01
% land forest	0.986	3.688
% land rocky	2.195	7.223
US bombs/ missiles/ rockets	16,725	43,421

Table 3: Reduced form effects of proximity to Ho Chi Minh Trail

Dependent variable:	△ ln expenditure per capita	△ ln expenditure per capita
Ln (proximity to Ho Chi Minh Trail)	0.0319**	0.0287***
	(0.0134)	(0.00808)
Full controls	Yes	Yes
Region FE	No	Yes
Observations	263	263
R-squared	0.511	0.617

Standard errors clustered at the province level. ***1%, **5%, *10% significance levels.

Dependent variable:	△ ln population	△ ln population
Ln (proximity to Ho Chi Minh Trail)	-0.0194	-0.0127
	(0.0215)	(0.0223)
Full controls	Yes	Yes
Region FE	No	Yes
Observations	263	263
R-squared	0.500	0.543

Standard errors clustered at the province level. ***1%, **5%, *10% significance levels.

Table 4: First stage regression results

Dependent variable:	ln (proximity to upgraded road)	ln (proximity to upgraded road)
ln (proximity to HCM Trail)	0.802***	0.842***
	(0.119)	(0.112)
Mean elevation (m)	0.00204***	0.00186***
	(0.000566)	(0.000672)
Mean slope (%)	0.0158	0.0171
	(0.0333)	(0.0387)
Average precipitation (cm)	-0.0184***	-0.0200***
	(0.00422)	(0.00367)
Average temperature (Celsius)	0.284	0.669**
	(0.204)	(0.271)
ln (dist to coast)	-0.0984	-0.105
	(0.135)	(0.159)
ln (land area)	-0.165	-0.137
	(0.299)	(0.301)
% land cultivated	-0.00835	-0.00378
	(0.00754)	(0.00759)
% land forest	-0.0193	-0.0339**
	(0.0144)	(0.0128)
% land rocky	0.0226*	0.0188*
	(0.0126)	(0.0102)
ln (dist to Hanoi or HCMC)	-0.758***	-0.731**
	(0.221)	(0.284)
US bombs/ missiles/ rockets	-3.71e-07	-5.70e-07
	(2.05e-06)	(2.00e-06)
Province capital	0.0620	0.0404
	(0.216)	(0.231)
ln (population 2000)	0.302	0.299
	(0.248)	(0.259)
Poverty rate 2000	-2.504*	-4.625***
	(1.334)	(1.466)
Literacy rate 1999	-1.011	-2.932**
	(1.851)	(1.352)
Urban share 1999	-0.344	-1.022
	(0.765)	(0.796)
Formal sector share 2000	-0.155	-0.293
	(3.457)	(3.485)
ln (weighted km roads 2000)	0.0912	-0.0129
	(0.379)	(0.412)
Observations	263	263
R-squared	0.391	0.437
Region FE	No	Yes
F test	45.52	56.82

Standard errors clustered at the province level. ***1%, **5%, *10% significance levels.

Table 5: Effects of proximity to upgraded roads

Dependent variable: △ ln expenditure per capita	OLS	OLS	IV	IV
Ln (proximity to upgraded road)	0.0125	0.0123	0.0398**	0.0341***
	(0.00957)	(0.00855)	(0.0185)	(0.0112)
Observations	263	263	263	263
R-squared	0.499	0.612	0.444	0.580
Full controls	Yes	Yes	Yes	Yes
Region FE	No	Yes	No	Yes

Standard errors clustered at the province level. ***1%, **5%, *10% significance levels.

Dependent variable: △ ln population	OLS	OLS	IV	IV
Ln (proximity to upgraded road)	-0.00344	-0.00256	-0.0242	-0.0151
	(0.0148)	(0.0137)	(0.0249)	(0.0245)
Observations	263	263	263	263
R-squared	0.496	0.541	0.479	0.536
Full controls	Yes	Yes	Yes	Yes
Region FE	No	Yes	No	Yes

Standard errors clustered at the province level. ***1%, **5%, *10% significance levels.

Table 6: Model-derived estimation: first stage regression results

Dependent variable:	△ ln market access	△ ln market access
ln (proximity to HCM Trail)	0.0454***	0.0483***
	(0.0137)	(0.0124)
Mean elevation (m)	0.0000984	0.0000177
	(0.0000731)	(0.0000727)
Mean slope (%)	-0.0018	0.00527
	(0.00478)	(0.0051)
Average precipitation (cm)	-0.000789*	-0.000968***
	(0.000389)	(0.000341)
Average temperature (Celsius)	0.0271	0.0677**
	(0.025)	(0.0263)
ln (dist to coast)	0.00331	0.00313
	(0.015)	(0.0138)
ln (land area)	0.0101	0.00417
	(0.0398)	(0.0345)
% land cultivated	-0.0000962	-0.0000973
	(0.00067)	(0.000653)
% land forest	-0.00485	-0.00489*
	(0.00288)	(0.00279)
% land rocky	-0.00156	-0.00135
	(0.00117)	(0.00116)
ln (dist to Hanoi or HCMC)	-0.0915***	-0.0866**
	(0.0262)	(0.0392)
US bombs/ missiles/ rockets	3.15e-07*	2.70e-07**
	(1.62e-07)	(1.21e-07)
Province capital	0.0169	0.0118
	(0.0418)	(0.0395)
ln (population 2000)	0.0809***	0.0757***
	(0.0241)	(0.0238)
Poverty rate 2000	-0.044	-0.171
	(0.162)	(0.25)
Literacy rate 1999	-0.19	-0.24
	(0.204)	(0.231)
Urban share 1999	0.198	0.174
	(0.133)	(0.132)
Formal sector share 2000	-0.478	-0.564
	(1.029)	(1.034)
ln (weighted km roads 2000)	-0.0751*	-0.0518
	(0.0438)	(0.0451)
Observations	263	263
R-squared	0.339	0.362
Region FE	No	Yes
F test	10.97	15.03

Standard errors clustered at the province level. ***1%, **5%, *10% significance levels.

Table 7: Model-derived estimation: effects of market access changes

Dependent variable: △ ln expenditure per capita	OLS	OLS	IV	IV
△ ln market access	0.241**	0.211***	0.703***	0.595***
	(0.0919)	(0.0707)	(0.251)	(0.156)
Observations	263	263	263	263
R-squared	0.547	0.646	0.327	0.499
Full controls	Yes	Yes	Yes	Yes
Region FE	No	Yes	No	Yes

Standard errors clustered at the province level. ***1%, **5%, *10% significance levels.

Table 8: Structural simulation of reduced form results

Panel A: Assuming district-level productivities constant over time

Dependent variable:	△ ln expenditure per capita
△ ln market access	0.143***
	(0.000)
Observations	271
R-squared	1

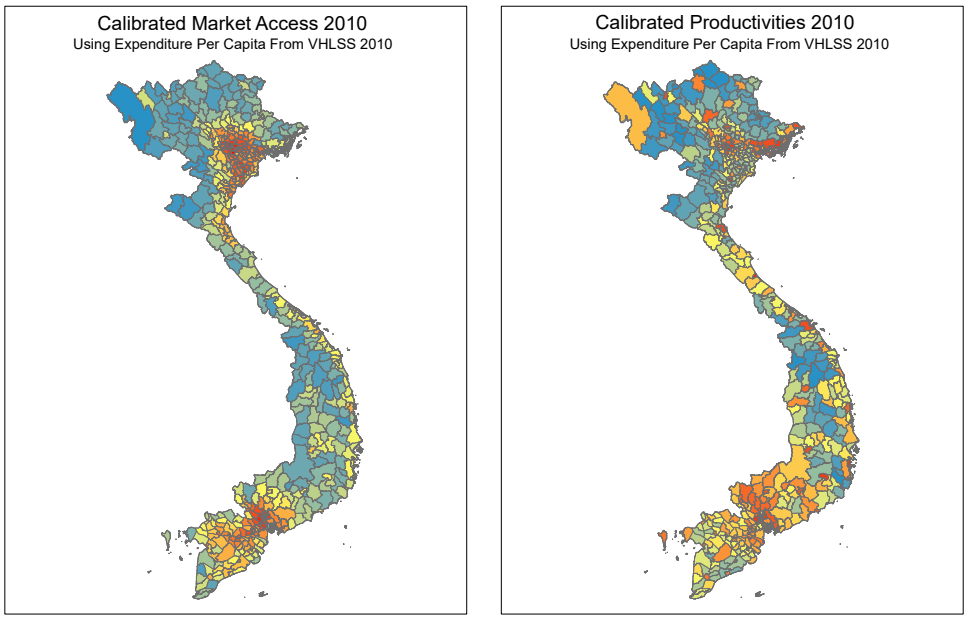
Standard errors clustered at the province level. ***1%, **5%, *10% significance levels.

Panel B: Using district-level productivities calibrated from 2000 data

Dependent variable:	△ ln expenditure per capita
△ ln market access	0.792***
	(0.253)
Observations	271
R-squared	0.256

Standard errors clustered at the province level. ***1%, **5%, *10% significance levels.

Figure 7: Calibrated market access and productivities in 2010



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

Table 9: Correlation between calibrated productivities and TFP

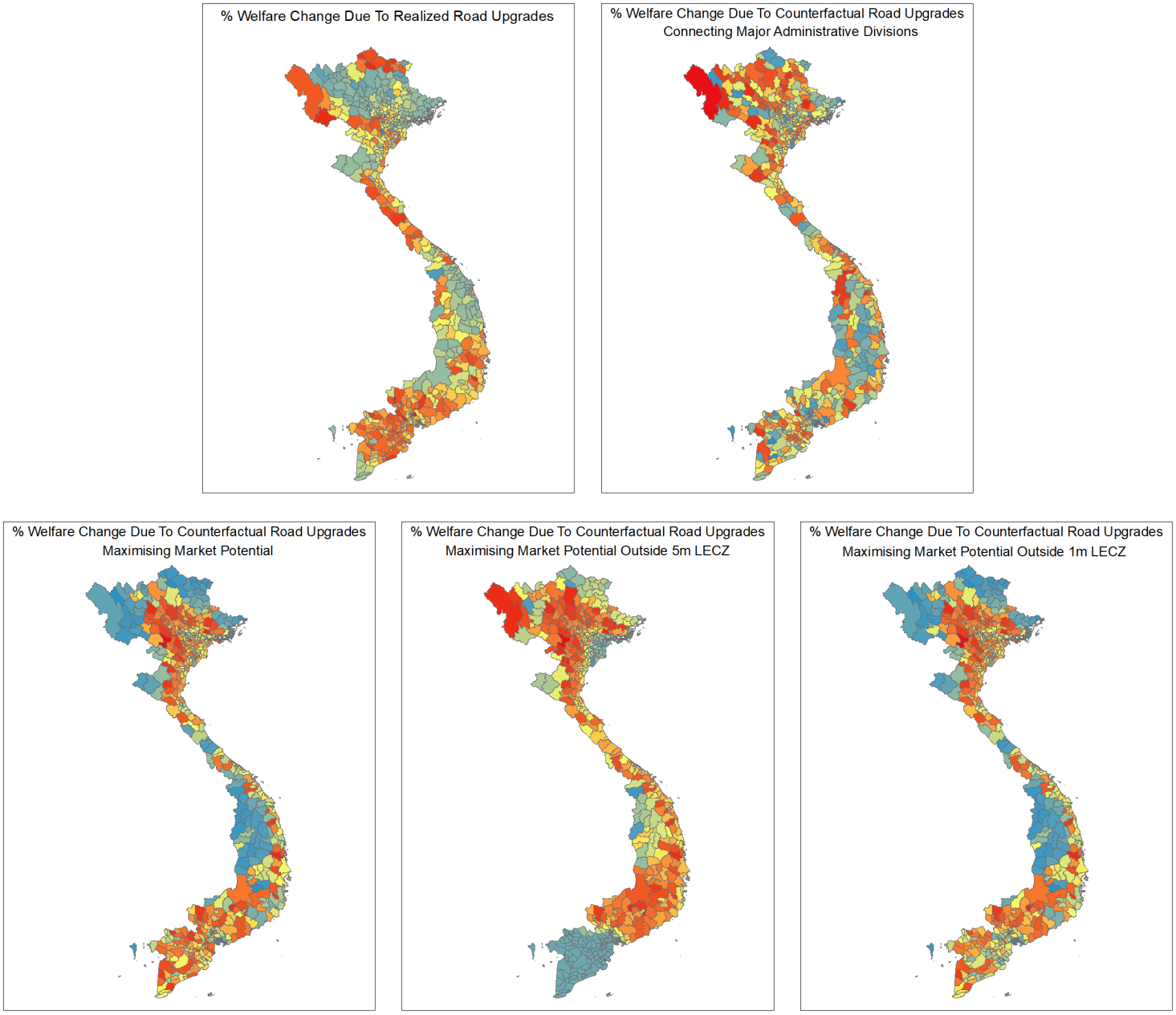
Dependent variable: Calibrated relative productivity level by district, 2010		
TFP estimated using $Y = AK^{\frac{1}{3}}L^{\frac{2}{3}}$	0.182***	
	(0.0207)	
TFP estimated using $Y = AL$		0.0386***
		(0.00438)
Observations	540	540
R-squared	0.126	0.126

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

Figure 8: Population changes induced by road investment scenarios

Data are reported at the level of district-based spatial units.
Red (blue) spatial units indicate higher (lower) values.
All results relative to baseline scenario of no investments in road upgrades in scenario with no future sea level rise.

Figure 9: Welfare changes induced by road investment scenarios



Data are reported at the level of district-based spatial units.
Red (blue) spatial units indicate higher (lower) values.
All results relative to baseline scenario of no investments in road upgrades
in scenario with no future sea level rise.

Figure 10: Vietnam road map 2010 and road upgrades 2000-2010

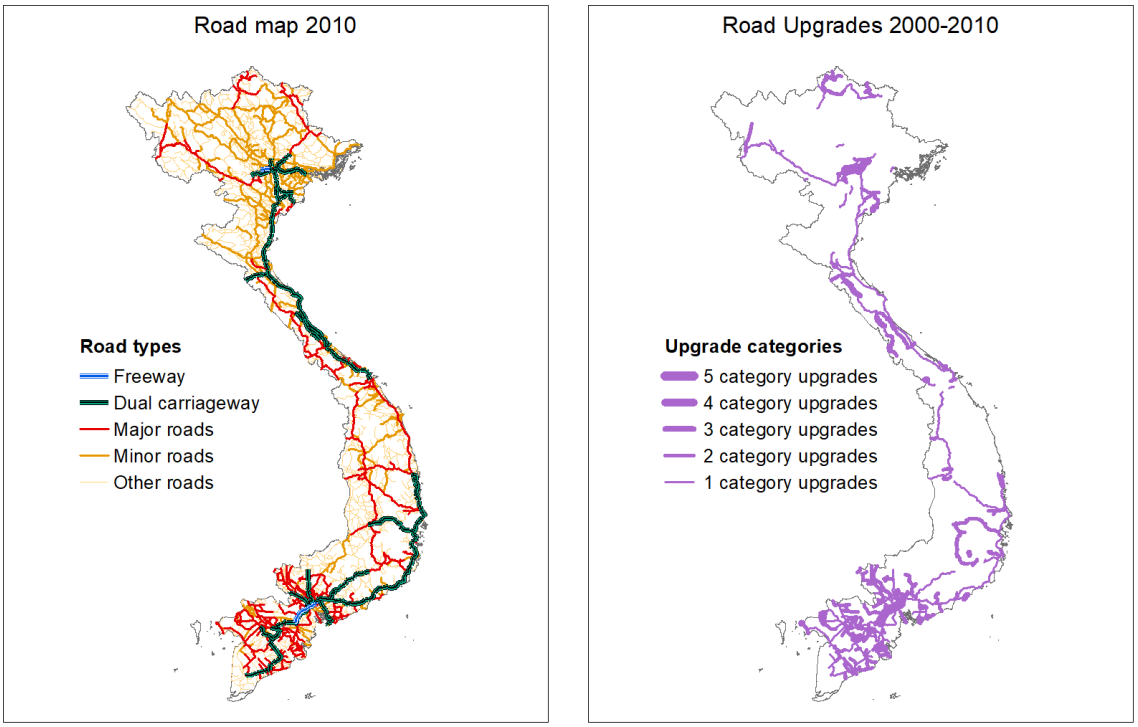


Figure 11: Counterfactual connecting major administrative divisions

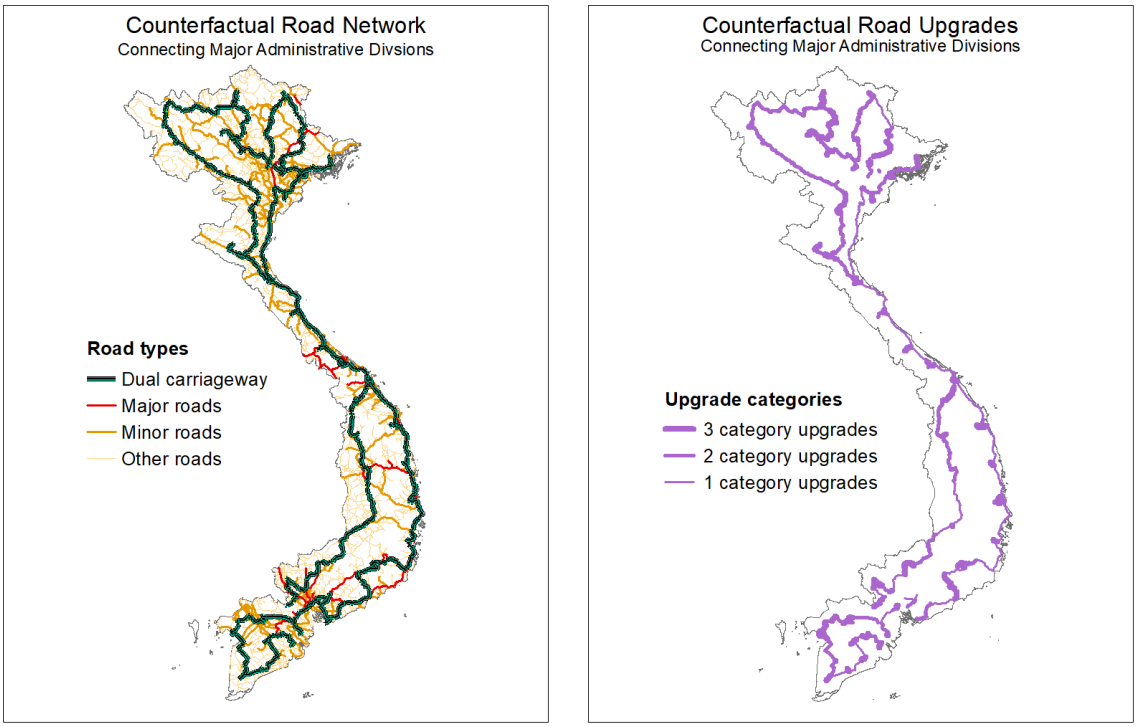


Figure 12: Counterfactual maximising market potential

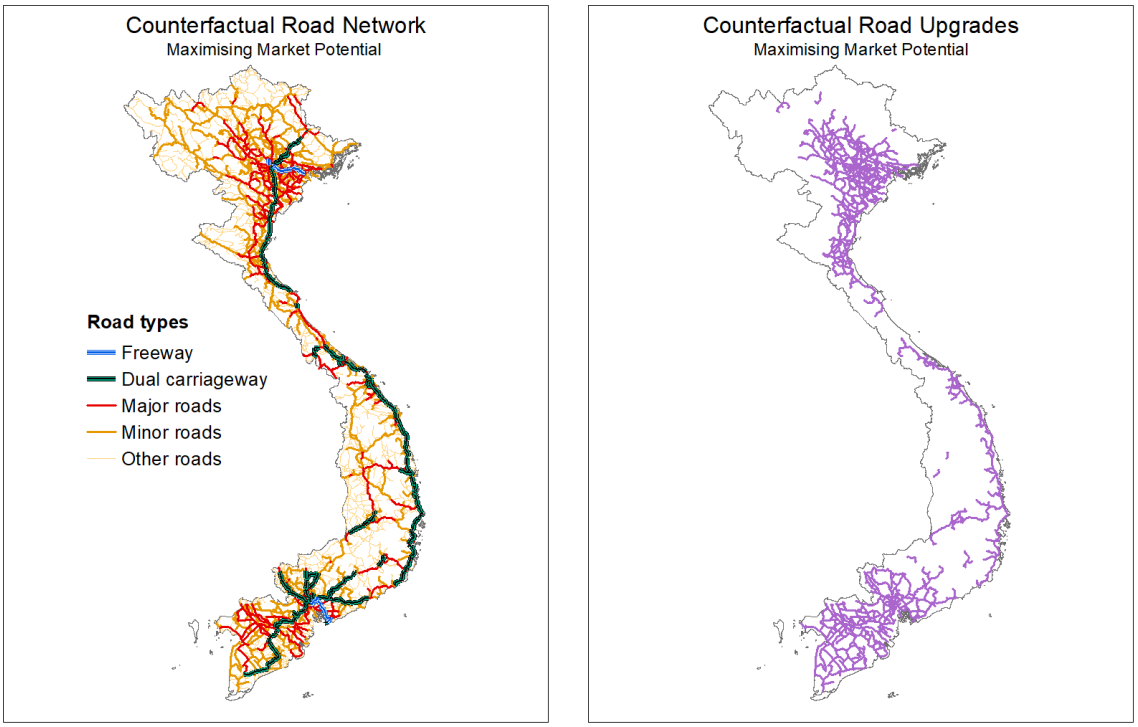


Figure 13: Counterfactual maximising market potential outside 5m coastal zone

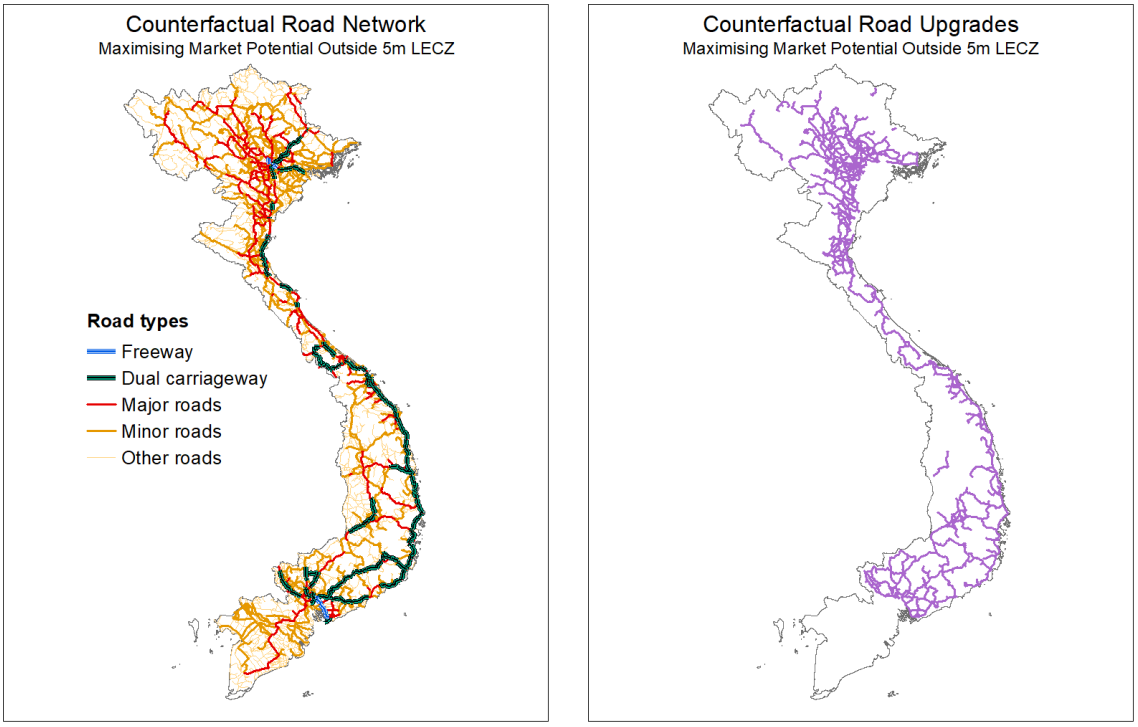


Figure 14: Counterfactual maximising market potential outside 1m coastal zone

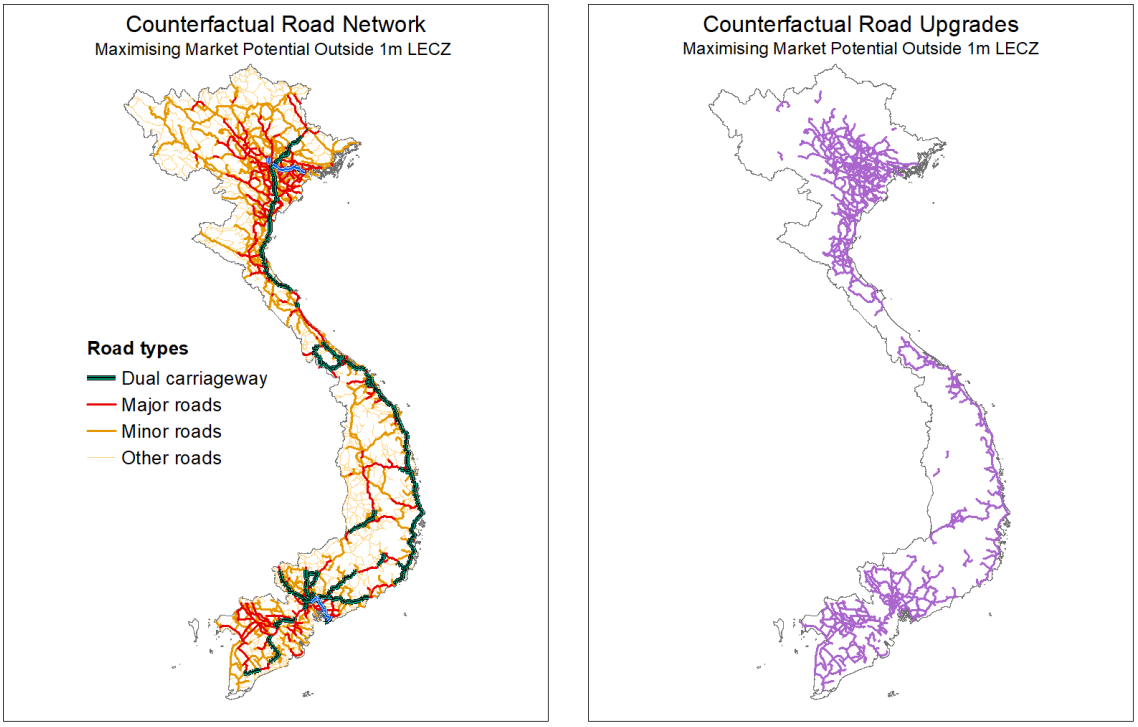


Figure 15: Welfare gains from counterfactual road investments with 1m sea level rise over 100 years

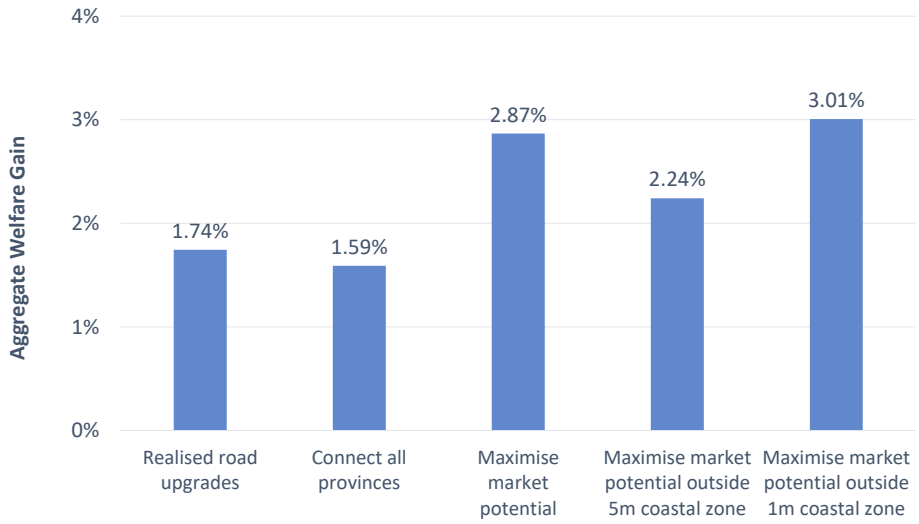


Figure 16: Welfare gains from counterfactual road investments without sea level rise

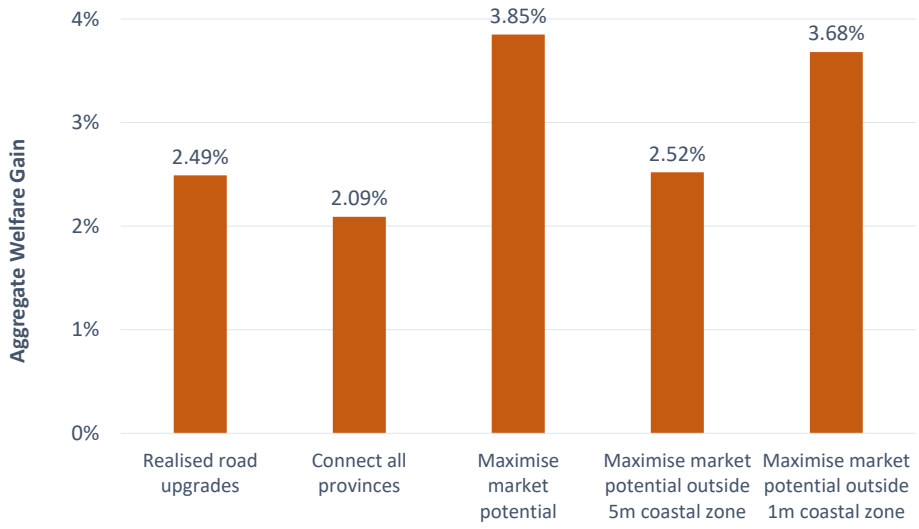


Figure 17: Relative welfare gains from counterfactual road investments

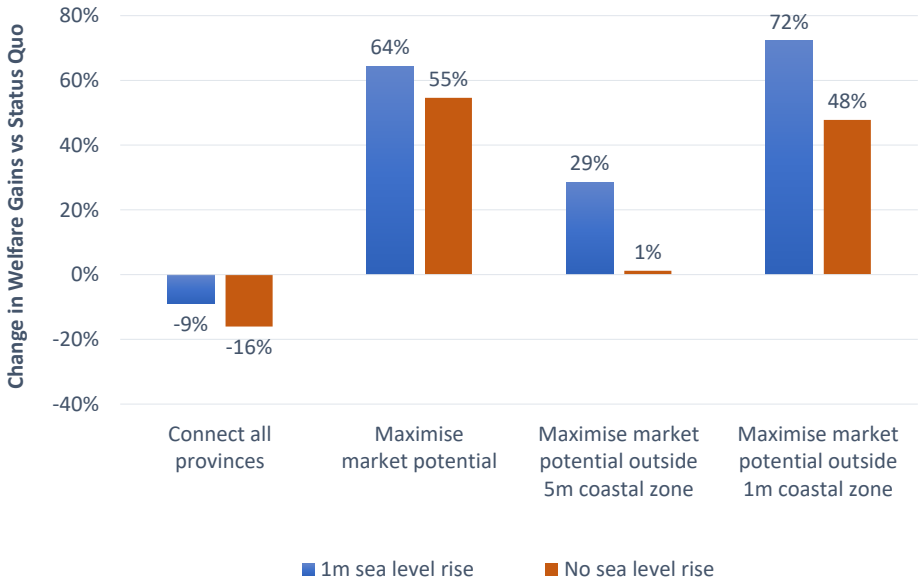


Figure 18: Relative welfare gains with changing coastal amenity premium

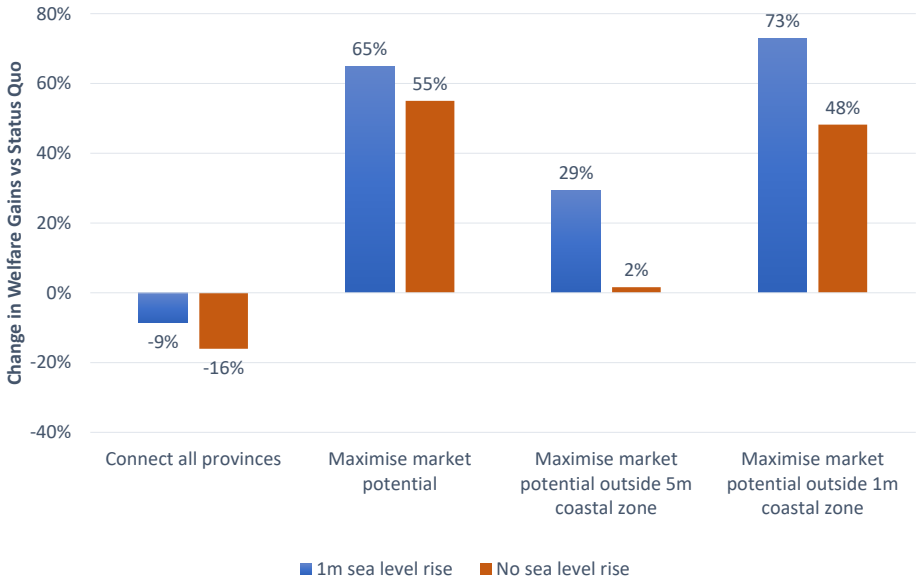


Figure 19: Relative welfare gains with secular change in productivities

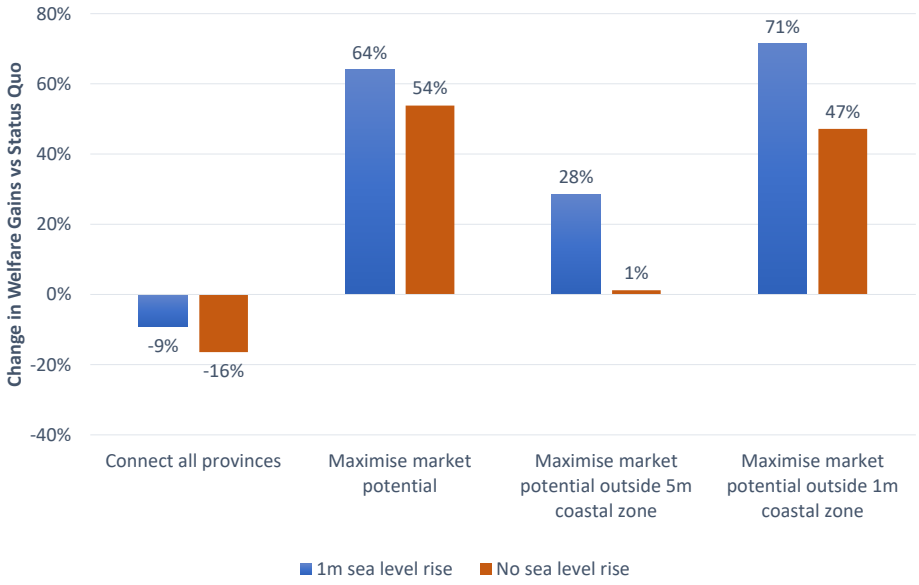


Figure 20: Relative welfare gains with changing international trade

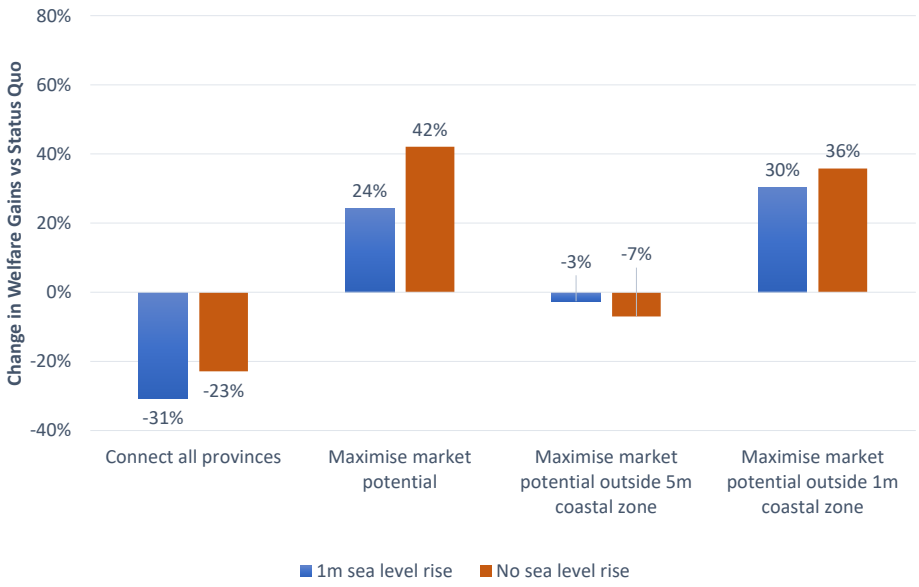


Figure 21: Relative welfare gains with unanticipated sea level rise

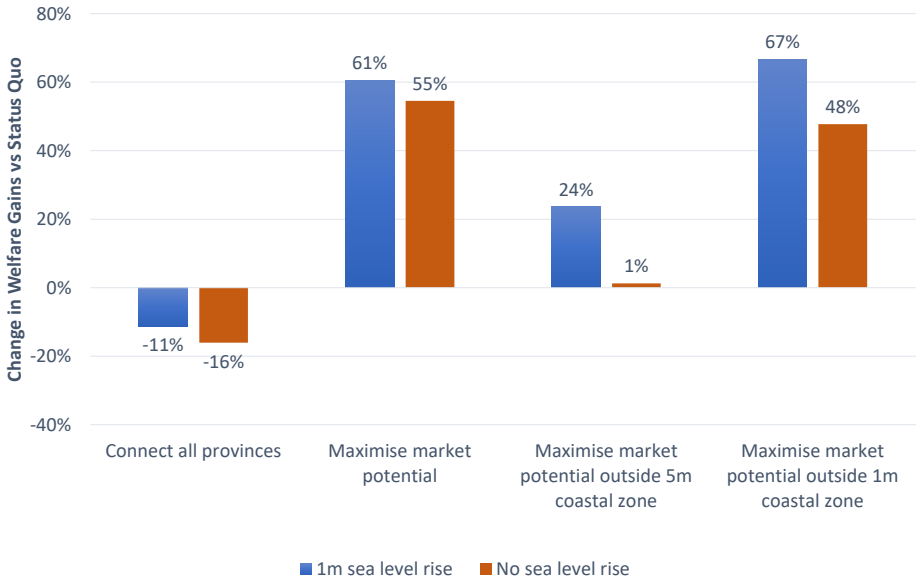


Figure 22: Relative welfare gains with depreciation of road investments

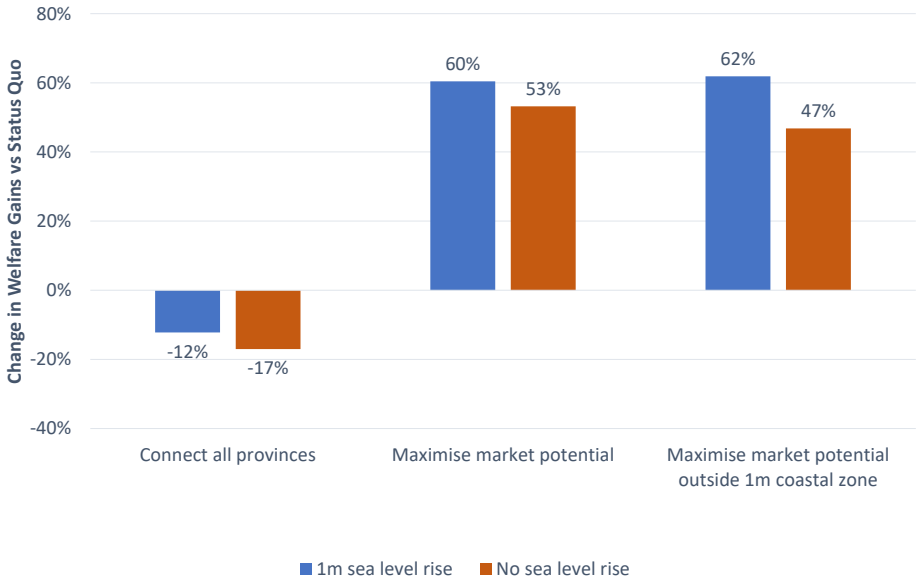


Figure 23: Relative welfare gains with alternative discount factor

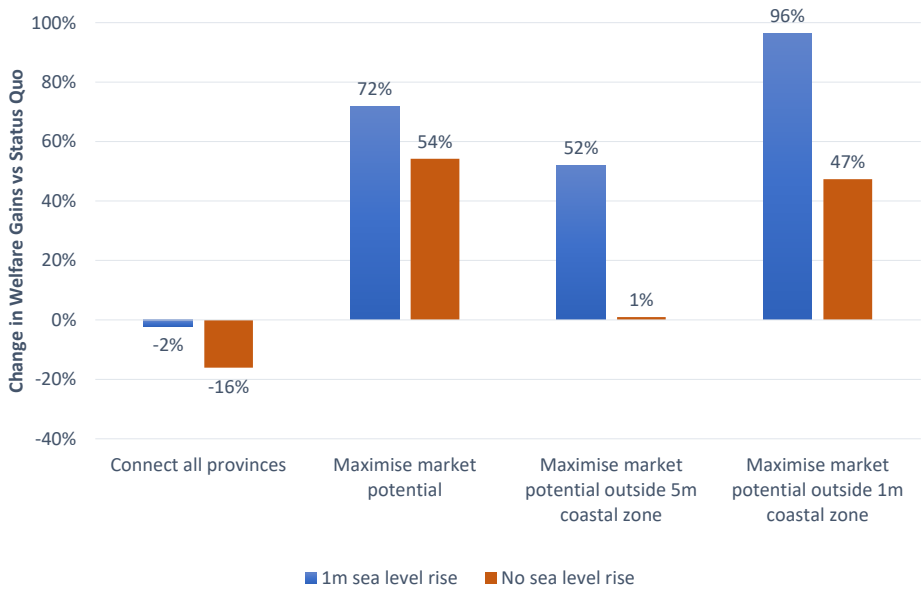
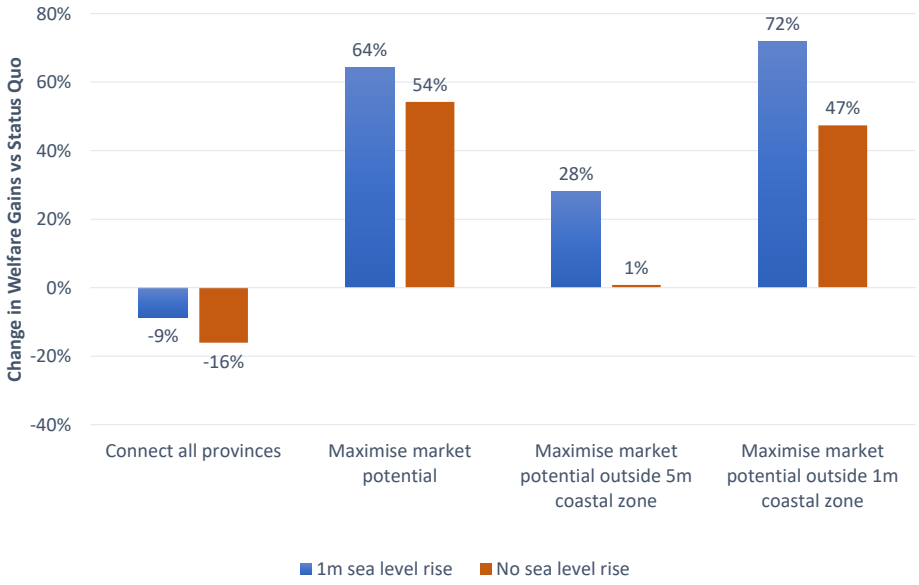


Figure 24: Relative welfare gains using formal sector wage



A Data Appendix: Transport Network Data

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

A.1 Roads

I obtain road network data from the 2000 and 2010 editions of ITMB Publishing's detailed International Travel Maps of Vietnam, which show the location of freeways, dual carriageways, major, minor and other roads. I geo-referenced each map and manually traced the location of each road category to obtain a GIS shapefile of the entire road network in each road category in 2000 and 2010, shown in Figure 5. The total length of the road network captured in this exercise is 45,741km in 2000 and 45,770km in 2010. National transport studies in 2000 and 2010 (JICA (2000), JICA (2010)) report the total lengths of roads at the national (15,250km in 2000/ 17,000km in 2010), provincial (17,449km/ 23,000km), district (36,372km/ 55,000km) and commune/village (131,455km/ 141,000km) level. As such, the road network data used in this analysis should cover the entire national and provincial road networks, and a sizeable share of of the district network. Since the object of interest for my analysis is the road network that facilitates trade and migration between spatial units at a slightly more aggregated level that the district level, the coverage of my road data seems sensible.

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

road), surface slope and surface condition.

To obtain speed data, I first assign each segment of road in 2000 and 2010 a designed speed based on its type and slope, and then adjust these downwards to obtain realised speeds based on a calibrated value for the average road surface condition across the network. I obtain road types from the mapped road networks. Surface slope is calculated using the elevation data described in Section 2.1.1 and the 'Slope' tool in ArcGIS Spatial Analyst, and discretised into three bins to denote flat, hilly and mountainous terrain[37]. JICA (2000) presents data on the designed speed for different road types in flat, hilly and mountainous regions. For comparability with this data, I assume that the freeways mapped in my road transport network correspond to roads with 4 x 3.75m lanes, dual carriageways to 2 x 3.75m lanes, major roads to 2 x 3m lanes, minor roads to 1 x 3.5m lanes and other roads to 1 x 3m lanes.

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

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

which corresponds to sub-national level roads) in 2010 is 40 km/hr. This calculation suggests that on average 72% of the designed speed is achieved, corresponding to fair road surface conditions according to the JICA (2000) descriptions. This is consistent with evidence in JICA (2010) that 43% of national highways were in good condition, 37% average and 20% bad or very bad. To calculate realised travel speeds on each segment of the road network, I therefore assume that road surface conditions are such that 72% of the designed speed can be achieved in both 2000 and 2010 (note that average speeds still increase significantly due to substantial road upgrades). Based on this and the designed speed for roads of different types and slopes, I assign a travel speed to each segment of the road network in 2000 and 2010.

I use JICA (2000) data on average truck mobilisation costs and cargo transportation costs per ton-km in 2000. I assume that the mobilisation cost is constant across the road network but that the average cost per ton-km applies at the average travel speed on the network of roads used by truckers (32km/hr in 2000). I then apply estimated adjustment factors to allow the cost per ton-km to vary at different road speeds[38]. To obtain 2010 figures, I use evidence from Blancas and El-Hifnawi (2013) that the cost per ton of cargo transport over the 4000km round trip along the North-South axis in 2010 was $110.5. I assume that the proportion of this attributable to mobilisation charges is the same in 2010 as in 2000 and that the cost per ton-km again applies at the average travel speed across the road network used by truckers (40 km/hr in 2010), scaling by the adjustment factors to obtain costs per ton-km at different road speeds.

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

A.2 Inland waterways

In contrast to the road network, the inland waterway network did not change significantly over the study period (JICA (2000), JICA (2010))[39]. I therefore map only one version of the inland waterway network, and use this for both the 2000 and 2010 analyses. The inland waterway network was traced manually in GIS from maps of the network in the JICA (2000) technical report on inland waterways, which shows the location of inland waterways in each of six classes characterised by different dimensions and therefore vessel capacities. This network was also cross-referenced with dimensions for major inland waterway routes in 2009 reported in Blancas and El-Hifnawi (2013) to verify that the network and channel classifications remained broadly unchanged. The inland waterway network is shown in Figure 25.

Blancas and El-Hifnawi (2013) estimate that the average sailing speed of self-propelled barges of all sizes on the inland waterway network is 9 km/hr, slightly lower than the typical design speed of 10 km/hr. Given minimal changes in the inland waterway network between 2000 and 2010, this value is used in both years. Blancas and El-Hifnawi (2013) provide estimates of 2010 loading and unloading costs per ton for inland waterway transportation and cargo transport costs per ton-km for ships of varying capacities[40]. For 2010 calculations, I assign the former as the mobilisation cost for all inland waterway journeys, and assign variable costs per ton-km based on the vessel capacities permissible on waterways of different classes. JICA (2000) provides average estimates in 2000 for mobilisation charges per ton (again assigned to all inland waterway journeys) and transport costs per ton-km. To calculate variable costs in 2000, I assume that the midpoint of the JICA (2000) figures applies to Class 3 waterways, and obtain values for

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

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

other waterway classes using the ratios of variable costs per ton-km across waterway classes from the 2010 data.

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

A.3 Coastal shipping

Coastal shipping routes are mapped based on the location of Vietnam's sea ports in 2000 and 2010. The locations of ports are taken from the website of the Vietnam Seaports Association. Data on which ports were operational and the maximum vessel sizes that were accepted in each port in 2000 and 2010 are based on the *'List of Seaports in the Master Plan on the Development of Vietnam's Seaport System till the Year 2010'*, *'List of Seaports in the Master Plan on Development of Vietnam's Seaport System through 2020'* and Blancas and El-Hifnawi (2013)[41]. The location of sea ports in 2000 and 2010 are shown in Figure 25, which also shows coastal shipping routes between them.

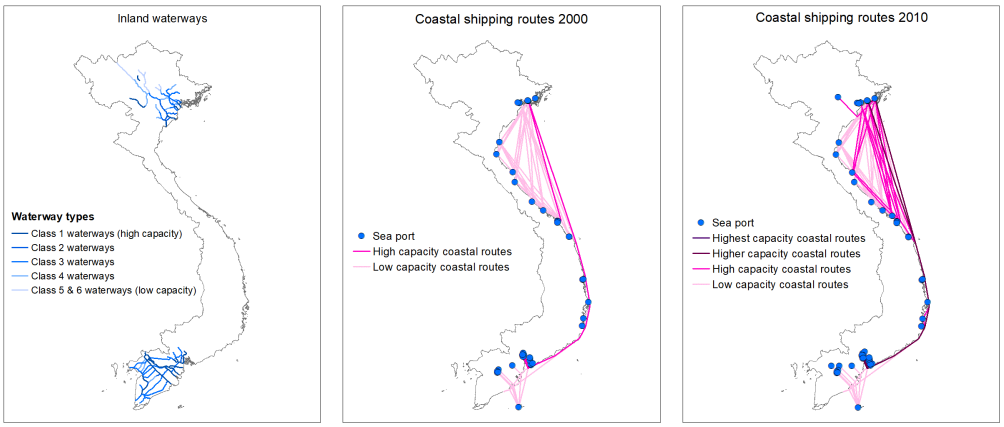
To map coastal shipping routes between these sea ports, I obtained the entire coastline of mainland Vietnam was obtained from Natural Earth and for both the 2000 and 2010 networks of seaports mapped the shortest route between neighbouring ports. Estimates of coastal shipping speeds are based on data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

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

travel speed of 19km/hr. This is used as the average coastal shipping speed on all routes in both 2000 and 2010 calculations.

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

Figure 25: Inland waterway and coastal shipping networks



The key data sources for the economic cost calculations are again JICA (2000), which reports average values for coastal shipping costs per ton-km and mobilisation charges in 2000, and Blancas and El-Hifnawi (2013), which provides 2010 shipping costs per ton for the Haiphong - Ho Chi Minh City route for vessels of different sizes. For 2000 calculations, I assume that the

JICA (2000) figures for variable costs and mobilisation charges are for a vessel of average size. I estimate these costs for vessels of other sizes by assuming that shipping costs per ton decrease with vessel size at the same rate as demonstrated in the 2010 data for the Haiphong - Ho Chi Minh City route, and that these decreases apply equally to mobilisation charges and variable costs. For 2010 calculations, I use the Blancas and El-Hifnawi (2013) data on total shipping costs per ton for the Haiphong - Ho Chi Minh City route by vessel size, and the share of mobilisation costs implied by the 2000 data[42]. The relevant variable transport cost per ton-km is assigned to each stretch, but the assigned mobilization cost on all routes is an average for the relevant year.

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

A.4 International seaports

The subset of seaports that are international seaports are obtained using data on domestic and international throughput at Vietnam's seaports in 2000 and 2010 from the Vietnam Seaports Association. In each year, I classify a seaport as an international seaport if it accounts for over 1% of the country's entire international cargo throughput and/or over 50% of the port's throughput is international in the relevant year. By this definition, the international seaports considered account for 98% of the country's total international cargo throughput in each year.

For the robustness tests allowing for international trade via land border crossings of the Asian Highway Network as well as international seaports, I obtain the location of these border crossings from maps of the Asian Highway

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

Network published by the United Nations Economic and Social Commission for Asia and the Pacific.

A.5 Connecting roads

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

B Solution algorithm with unanticipated sea level rise

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

In this case, the solution method uses agents' behaviour before the arrival of the shock to construct differenced equations for $Y_{n,t+1}$, $\frac{m_{in,t+1}}{m_{in,t}}$ and $L_{n,t}$, which can be used together with equilibrium conditions (21) and (22) to solve for the sequential competitive equilibrium. Let $X\left(\Theta^{s}\right)$ denote the variable X according to the information available in period s. Recall that at $t = 0$ (2010), agents expect gradual inundation over the periods $t = 1$ to $t = 9$, with sea levels maintained at their $t = 9$ levels thereafter. At $t = 10$ (2060), agents learn that the gradual inundation will instead continue. Take as given the set of initial conditions $L_{n,0}$, $m_{in,-1}$ and $w_{n,0}$; the assumed path for the values of the model's parameters $\{H_{n,t}\}_{t=0}^{T}$, $\left\{\left(\frac{1}{F}\right)^{\frac{1}{\sigma-1}} A_{n,t}\right\}_{t=0}^{T}$, $\{E_{n,t}\}_{t=0}^{T}$, $\{d_{ni,t}\}_{t=0}^{T}$ and $\{d_{xn,t}\}_{t=0}^{T}$ based on the information available during each time period; and the solution (computed previously) to the sequential competitive equilibrium in the absence of any shocks. In this case, the equilibrium conditions for $Y_{n,t+1}$, $\frac{m_{in,t+1}}{m_{in,t}}$ and $L_{n,t}$ are derived at Appendix C and summarised here.

The equilibrium conditions for expected lifetime utility and migration shares expressed in relative time differences in the absence of any shocks are

as derived previously (equations 30 and 31), repeated here with the available information set made explicit:

$$
\begin{aligned}
Y\left(\Theta^{0}\right)_{n,t+1} &= \left[\frac{\left(\frac{w\left(\Theta^{0}\right)_{n,t+1}}{w\left(\Theta^{0}\right)_{n,t}}\right)^{\alpha}}{\left(\frac{P\left(\Theta^{0}\right)_{n,t+1}}{P\left(\Theta^{0}\right)_{n,t}}\right)^{\alpha}\left(\frac{L\left(\Theta^{0}\right)_{n,t+1}/L\left(\Theta^{0}\right)_{n,t}}{H\left(\Theta^{0}\right)_{n,t+1}/H\left(\Theta^{0}\right)_{n,t}}\right)^{1-\alpha}}\right]^{\frac{1}{\nu}} \\
&\quad \times \sum_{k\in N} m\left(\Theta^{0}\right)_{kn,t}\left(Y\left(\Theta^{0}\right)_{k,t+2}\right)^{\beta} \\
&\quad \times exp\left[\frac{1}{\nu}\left(B\left(\Theta^{0}\right)_{k,t+1}-B\left(\Theta^{0}\right)_{k,t}\right)\right]
\end{aligned}
\tag{35}
$$

$$
\frac{m\left(\Theta^{0}\right)_{in,t+1}}{m\left(\Theta^{0}\right)_{in,t}} = \frac{\left(Y\left(\Theta^{0}\right)_{i,t+2}\right)^{\beta}\left(exp\left[B\left(\Theta^{0}\right)_{i,t+1}-B\left(\Theta^{0}\right)_{i,t}\right]\right)^{\frac{1}{\nu}}}{\sum_{k\in N} m\left(\Theta^{0}\right)_{kn,t}\left(Y\left(\Theta^{0}\right)_{k,t+2}\right)^{\beta}\left(exp\left[B\left(\Theta^{0}\right)_{k,t+1}-B\left(\Theta^{0}\right)_{k,t}\right]\right)^{\frac{1}{\nu}}} \tag{36}
$$

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

$$
\begin{aligned}
Y\left(\Theta^{10}\right)_{n,10} &= \left[\frac{\left(\frac{w\left(\Theta^{10}\right)_{n,10}}{w\left(\Theta^{0}\right)_{n,9}}\right)^{\alpha}}{\left(\frac{P\left(\Theta^{10}\right)_{n,10}}{P\left(\Theta^{0}\right)_{n,9}}\right)^{\alpha}\left(\frac{L\left(\Theta^{10}\right)_{n,10}/L\left(\Theta^{0}\right)_{n,9}}{H\left(\Theta^{10}\right)_{n,10}/H\left(\Theta^{0}\right)_{n,9}}\right)^{1-\alpha}}\right]^{\frac{1}{\nu}} \\
&\quad + \sum_{i\in N}\left(\frac{Y\left(\Theta^{10}\right)_{i,10}}{Y\left(\Theta^{0}\right)_{i,10}}\right)^{\beta} m\left(\Theta^{0}\right)_{in,9}\left(Y\left(\Theta^{10}\right)_{i,11}\right)^{\beta} \\
&\quad \times\left(exp\left[B\left(\Theta^{10}\right)_{i,10}-B\left(\Theta^{0}\right)_{i,9}\right]\right)^{\frac{1}{\nu}}
\end{aligned}
\tag{37}
$$

$$Y\left(\Theta^{10}\right)_{n,t+1} = \left[\frac{\left(\frac{w\left(\Theta^{10}\right)_{n,t+1}}{w(\Theta^{10})_{n,t}}\right)^{\alpha}}{\left(\frac{P(\Theta^{10})_{n,t+1}}{P(\Theta^{10})_{n,t}}\right)^{\alpha}\left(\frac{L(\Theta^{10})_{n,t+1}/L(\Theta^{10})_{n,t}}{H(\Theta^{10})_{n,t+1}/H(\Theta^{10})_{n,t}}\right)^{1-\alpha}}\right]^{\frac{1}{\nu}} \times \sum_{k\in N} m\left(\Theta^{10}\right)_{kn,t}\left(Y\left(\Theta^{10}\right)_{k,t+2}\right)^{\beta} \times \left(exp\left[B\left(\Theta^{10}\right)_{i,t+1} - B\left(\Theta^{10}\right)_{i,t}\right]\right)^{\frac{1}{\nu}}, \quad t \geq 10 \tag{38}$$

$$\frac{m\left(\Theta^{10}\right)_{in,10}}{m(\Theta^{0})_{in,9}} = \frac{\left(Y\left(\Theta^{10}\right)_{i,11}\right)^{\beta}\left(\frac{Y\left(\Theta^{10}\right)_{i,10}}{Y(\Theta^{0})_{i,10}}\right)^{\beta}\left(exp\left[B\left(\Theta^{10}\right)_{i,10} - B\left(\Theta^{0}\right)_{i,9}\right]\right)^{\frac{1}{\nu}}}{\sum_{k\in N} m(\Theta^{0})_{kn,9}\left(Y(\Theta^{10})_{k,11}\right)^{\beta}\left(\frac{Y(\Theta^{10})_{k,10}}{Y(\Theta^{0})_{k,10}}\right)^{\beta}\left(exp\left[B(\Theta^{10})_{k,10} - B(\Theta^{0})_{k,9}\right]\right)^{\frac{1}{\nu}}} \tag{39}$$

$$\frac{m(\Theta^{10})_{in,t+1}}{m(\Theta^{10})_{in,t}} = \frac{\left(Y(\Theta^{10})_{i,t+2}\right)^{\beta}\left(exp\left[B(\Theta^{10})_{i,t+1} - B(\Theta^{10})_{i,t}\right]\right)^{\frac{1}{\nu}}}{\sum_{k\in N} m(\Theta^{10})_{kn,t}\left(Y(\Theta^{10})_{k,t+2}\right)^{\beta}\left(exp\left[B(\Theta^{10})_{k,t+1} - B(\Theta^{10})_{k,t}\right]\right)^{\frac{1}{\nu}}}, \quad t > 10 \tag{40}$$

$$L\left(\Theta^{10}\right)_{n,10} = \sum_{i\in N} m\left(\Theta^{9}\right)_{ni,9} L\left(\Theta^{9}\right)_{i,9} \tag{41}$$

$$L\left(\Theta^{10}\right)_{n,t+1} = \sum_{i\in N} m\left(\Theta^{10}\right)_{ni,t} L\left(\Theta^{10}\right)_{i,t}, \quad t > 10 \tag{42}$$

This is the set of equilibrium conditions that are solved together with equilibrium conditions (21), (22) and (25) for the sequential competitive equilibrium in the case where sea level rise arrives as an unanticipated shock.

C Theory Appendix

Derivation of equation (3) for expected lifetime utility:

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

$$\begin{aligned}
V_{n,t} &= \alpha ln\left(\tfrac{C_{n,t}}{\alpha}\right) + (1-\alpha) ln\left(\tfrac{H_{n,t}}{1-\alpha}\right) + \mathbb{E}\left\{max_{i\in N}\left[\beta\mathbb{E}\left(v_{i,t+1}\right) - \mu_{in} + B_{i,t} + b_{i,t}\right]\right\} \\
&= \alpha ln\left(\tfrac{C_{n,t}}{\alpha}\right) + (1-\alpha) ln\left(\tfrac{H_{n,t}}{1-\alpha}\right) + \mathbb{E}\left\{\textstyle\sum_{i\in N}\left(\beta V_{i,t+1} - \mu_{in} + B_{i,t} + b_{i,t}\right)\right\} \times \\
&\quad Pr\left[\left(\beta V_{i,t+1} - \mu_{in} + B_{i,t} + b_{i,t}\right) \geq \left(\beta V_{m,t+1} - \mu_{mn} + B_{m,t} + b_{m,t}\right), m = 1, ..., N\right] \\
&= \alpha ln\left(\tfrac{C_{n,t}}{\alpha}\right) + (1-\alpha) ln\left(\tfrac{H_{n,t}}{1-\alpha}\right) + \textstyle\sum_{i\in N}\int\left(\beta V_{i,t+1} - \mu_{in} + B_{i,t} + b_{i,t}\right) f\left(b_{i,t}\right) \\
&\quad \times \textstyle\prod_{m\neq i} F\left(\beta\left(V_{i,t+1} - V_{m,t+1}\right) - \left(\mu_{in} - \mu_{mn}\right) + \left(B_{i,t} - B_{m,t}\right) + b_{i,t}\right) db_{i,t} \\
&= \alpha ln\left(\tfrac{C_{n,t}}{\alpha}\right) + (1-\alpha) ln\left(\tfrac{H_{n,t}}{1-\alpha}\right) \\
&\quad + \textstyle\sum_{i\in N}\int\left(\beta V_{i,t+1} - \mu_{in} + B_{i,t} + b_{i,t}\right) f\left(b_{i,t}\right) \prod_{m\neq i} F\left(\bar{b_{im,t}} + b_{i,t}\right) db_{i,t}
\end{aligned} \tag{43}$$

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

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

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

and density function:

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

3. Substituting the cumulative distribution function and density function

into equation (43) yields the following::

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

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

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

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

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

Derivation of equation (4) for migration shares:

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

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

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

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

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

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

Derivation of equation (26) for welfare at location n at time t:

1. From equation (4), the share of the population who start period t in location n that choose to stay in the same location next period is given by:

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

which implies that:

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

2. Substituting this into equation (13) gives:

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

3. Iterating this equation forward yields:

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

4. Simplifying yields:

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

Derivation of equation (30) for the equilibrium condition for lifetime utilities expressed in relative differences:

1. From the equilibrium condition for expected lifetime utility in equation (23):

$$[exp\left(V_{n,t+1} - V_{n,t}\right)]^{\frac{1}{\nu}}$$

$$\begin{aligned} &= [exp\{\alpha ln\left(\frac{w_{n,t+1}}{\alpha}\right) - \alpha lnP_{n,t+1} - (1-\alpha)ln\left(\frac{(1-\alpha)L_{n,t+1}}{H_{n,t+1}}\right) \\ &\quad +\nu ln\sum_{i\in N}\left(exp\left[\beta V_{i,t+2} - \mu_{in} + B_{i,t+1}\right]\right)^{\frac{1}{\nu}} \\ &\quad -\left(\alpha ln\left(\frac{w_{n,t}}{\alpha}\right) - \alpha lnP_{n,t} - (1-\alpha)ln\left(\frac{(1-\alpha)L_{n,t}}{H_{n,t}}\right)\right) \\ &\quad -\nu ln\sum_{i\in N}\left(exp\left[\beta V_{i,t+1} - \mu_{in} + B_{i,t}\right]\right)^{\frac{1}{\nu}}\}]^{\frac{1}{\nu}} \end{aligned} \tag{44}$$

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

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

$$\frac{\sum_{i\in N}(exp[\beta V_{i,t+2}-\mu_{in}+B_{i,t+1}])^{\frac{1}{\nu}}}{\sum_{i\in N}(exp[\beta V_{i,t+1}-\mu_{in}+B_{i,t}])^{\frac{1}{\nu}}}$$

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

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

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

$$\frac{\sum_{i\in N}(exp[\beta V_{i,t+2}-\mu_{in}+B_{i,t+1}])^{\frac{1}{\nu}}}{\sum_{i\in N}(exp[\beta V_{i,t+1}-\mu_{in}+B_{i,t}])^{\frac{1}{\nu}}}$$

$$=m_{1n,t}\frac{(exp[\beta V_{1,t+2}-\mu_{1n}+B_{1,t+1}])^{\frac{1}{\nu}}}{(exp[\beta V_{1,t+1}-\mu_{1n}+B_{1,t}])^{\frac{1}{\nu}}}+m_{2n,t}\frac{(exp[\beta V_{2,t+2}-\mu_{2n}+B_{2,t+1}])^{\frac{1}{\nu}}}{(exp[\beta V_{2,t+1}-\mu_{2n}+B_{2,t}])^{\frac{1}{\nu}}}+...$$

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

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

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

4. Substituting this back into equation (44) gives:

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

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

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

Derivation of equation (31) for the equilibrium condition for migration shares expressed in relative differences:

1. From the equilibrium condition for migration shares in equation (24):

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

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

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

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

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

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

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

Derivation of equations (37) to (40) for the equilibrium conditions for lifetime utilities, migration shares and population with unanticipated sea level rise:

1. The assumptions made about how agents anticipate the evolution of the future path of sea level rise is as follows. At $t = 0$ (2010), agents expect gradual inundation over the periods $t = 1$ to $t = 9$, with sea levels maintained at their $t = 9$ levels thereafter. At $t = 10$, agents

learn that the gradual inundation will continue until $t = 20$ (2110), after which sea levels remain constant. Let $X\left(\Theta^{s}\right)$ denote the variable X according to the information available in period s.

2. Using the equilibrium conditions in relative time differences for expected lifetime utility in equation (30) and for migration shares in equation (31), the evolution of $\left\{m\left(\Theta^{0}\right)_{ni,t}, Y\left(\Theta^{0}\right)_{n,t+1}\right\}_{t=0}^{\infty}$ in the absence of any shocks can be obtained from:

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

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

3. No shocks occur during $0 \leq t \leq 9$. At $t = 10$, the shock is received and the information set $\left(\Theta^{10}\right)$ becomes available. Adding and subtracting $\beta V\left(\Theta^{10}\right)_{i,10}$ in the equations for $V\left(\Theta^{0}\right)_{i,9}$ and $m\left(\Theta^{0}\right)_{in,9}$ yields:

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

$$\begin{aligned} & m\left(\Theta^{0}\right)_{in,9} \\ & = \\ & \frac{\left(exp\left[V\left(\Theta^{0}\right)_{i,10} - V\left(\Theta^{10}\right)_{i,10}\right]\right)^{\frac{\beta}{\nu}}\left(exp\left[\beta V\left(\Theta^{10}\right)_{i,10} - \mu_{in} + B\left(\Theta^{0}\right)_{i,9}\right]\right)^{\frac{1}{\nu}}}{\sum_{k\in N}\left(exp\left[V\left(\Theta^{0}\right)_{k,10} - V\left(\Theta^{10}\right)_{k,10}\right]\right)^{\frac{\beta}{\nu}}\left(exp\left[\beta V\left(\Theta^{10}\right)_{k,10} - \mu_{kn} + B\left(\Theta^{0}\right)_{k,9}\right]\right)^{\frac{1}{\nu}}} \end{aligned} \tag{45}$$

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

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

$$m\left(\Theta^{10}\right)_{in,t} = \frac{\left(exp\left[\beta V\left(\Theta^{10}\right)_{i,t+1} - \mu_{in} + B\left(\Theta^{10}\right)_{i,t}\right]\right)^{\frac{1}{\nu}}}{\sum_{k\in N}\left(exp\left[\beta V\left(\Theta^{10}\right)_{k,t+1} - \mu_{kn} + B\left(\Theta^{10}\right)_{k,t}\right]\right)^{\frac{1}{\nu}}} \tag{46}$$

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

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

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

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

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

$Y\left(\Theta^{10}\right)_{n,t+1} = \left[exp\left(V\left(\Theta^{10}\right)_{n,t+1} - V\left(\Theta^{10}\right)_{n,t}\right)\right]^{\frac{1}{\nu}}$ yields:

$$Y\left(\Theta^{10}\right)_{n,10}$$
$$=$$
$$exp\left[\frac{1}{\nu}\left(V\left(\Theta^{10}\right)_{n,10} - V\left(\Theta^{0}\right)_{n,9}\right)\right]$$

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

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

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

7. Taking equation (46) for $m\left(\Theta^5\right)_{in,10}$ and dividing by the expression for

$m\left(\Theta^{0}\right)_{in,9}$ in equation (45) yields:

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

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

8. In time periods after $t = 10$, the same method as was used to prove equations (30) and (31) can be used to show that:

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

and:

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

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

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

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

and:

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

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