Dynamic General Equilibrium Model – Climate Resilient Economic Development (DGE-CRED)* Vietnam Case Study

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Abstract

This paper applies a dynamic general equilibrium model for climate resilient economic development (DGE-CRED) with multiple sectors and regions for Vietnam. Sector and region-specific damage functions are calibrated according to scientific studies and expert knowledge that quantify the impact of climate variables on the productivity of production factors or the formation of capital. The simulations and cost-benefit analyses that we perform with our model reflect the evolution of climate variables according to the shared socio-economic pathways (SSPs) 119, 245 and 585 scenarios. The application for Vietnam illustrates how to define biophysical damages, such as crop yield loss, and land losses due to sea-level rise into productivity losses for different sectors. Further, we show how to incorporate estimated monetary damages to capital and housing stock. In addition different adaptation options are evaluated. The results are well in line with Espagne et al. (2021). For the SSP 245 scenario the estimated reduction in annual GDP is roughly 5 percent by 2050. According to the results adaptation measures for the dyke system should have priority to reduce the consumption gap. However, we see that neither the considered adaptation measures targeting dykes, drainage systems, transport infrastructure, housing, and forestry nor the coffee sector can reduce the consumption gap to a relevant magnitude. It implies that damages induced on agriculture and labour productivity are the primary source of consumption reductions in Vietnam due to climate change. Policymakers in Vietnam should focus on adaptation measures for the agricultural sector and reduce labour intensity.

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Contents

List of Figures

List of Tables

1 Introduction

Projections by the international panel on climate change (IPCC) show that the global average temperature, the sea level and the frequency of weather extremes are likely to change as a consequence of higher greenhouse gas concentrations in the atmosphere all over the world Stocker et al. (2013). Vietnam belongs to the group of countries that are highly vulnerable to climate change, including negative consequences for their economic development. Previous studies (e.g. Arndt et al. 2015, Chen et al. 2012, Wassmann et al. 2004) show quantitatively that an increase in temperature, sea-level rise and a higher frequency of weather extremes (e.g. cyclones and droughts) are hazards to future economic development.

More recent studies evaluating the impact of climate change on Vietnam are Espagne et al. (2021) and World Bank Group (2022). Espagne et al. (2021) evaluates the impact of climate change using a stock-flow consistent model. The study includes damages to agriculture, energy, health, labour productivity and total factor productivity. All damages are derived from sector specific analysis for different regions in Vietnam. All damages are conditional on the realized change in temperature. Therefore, the model's impact channels from different climate variables are all synthesized to be represented by temperature. According to the results for the Reference concentration pathway (RCP) 4.5 and 8.5 climate change can cause a reduction in GDP between -5.4 (-0.7 to -10.4) percent and -7.8 (-1.7 to -12.2) percent, respectively. World Bank Group (2022) use the Mitigation, Adaptation, and New Technologies Applied General Equilibrium (MANAGE) to quantify the effect of climate change in Vietnam. The study finds that in the RCP 4.5 scenario, GDP declines by 9.45 percent until 2050. Compared to the effects by Arndt et al. (2015) more recent studies seem to find much larger impacts of climate change.[1] However, none of the more recent studies simulates regional heterogeneity of climate change impacts. Further, the present analysis directly incorporates adaptation measures to evaluate the macroeconomic impacts. National statistics differentiate between six different statistical regions in Vietnam: Red River Delta, Northern Midlands and Mountain Areas (North East and North West), North Central and Central Coastal area (North Central Coast and South Central Coast), Central Highlands, South East, and Mekong River Delta. The map in Figure 1 shows that four of the six regions are located at the coast. Hence, the impact of sea-level rise will be different for coastal and non-coastal regions in Vietnam.

Further, climate change will affect economic activities like agriculture, forestry and fishery differently than manufacturing. Climate variables have different effects on the production factors labour and capital used in the different economic sectors. Adaptation measures, i.e. measures that are aimed at reducing the negative impact of climate change on the economy, are thus designed to target different sectors and different production factors independently. Examples include the construction of raising houses on stilts reducing the damage by sea-level rise, replacing conventional asphalt with polymer asphalt concrete to make roads more resilient to extreme temperatures. Labour productivity can be affected by heat waves as well. Adaptation measures replacing labour-intensive tasks using more capital-intensive production processes are potential adaptation measures. A cost-benefit analysis is necessary to prioritise and evaluate different adaptation measures. The analysis needs to account for the dynamic nature of the problem, and future benefits need to be expressed in terms of todays' costs. It is also necessary to evaluate the sensitivity of the results to different assumptions made to get reasonable policy decisions. Further, the analysis needs to be transparent and all the assumptions made are explicitly stated. Structural mathematical models are a suitable tool for this task.

Dynamic general equilibrium models with optimising agents provide a consistent framework to assess the impact of different policy measures on variables of interest. Besides their principal purpose, adaptation measures will either reduce productivity in the short run by relocating economic activity or reduce available public funds for other development measures. Investment decisions today will affect the future development of specific sectors. This implies path dependency and requires a dynamic framework. We need to differentiate between different regions and economic activities to account for different regional climate developments.

We extend the approach by Nordhaus (1993) to model the impact of climate change on different economic sectors and regions of Vietnam. The sector and region-specific damage functions are calibrated according to scientific studies and expert knowledge that quantify the impact of climate variables on the productivity of production factors or the formation of capital. The simulations and cost-benefit analyses that we perform with our model will use the results of meteorology models to define paths for

[1] A direct comparison is not straightforward. Arndt et al. (2015) states cumulate effects of climate change on GDP and not effects on annual GDP.

climate variables. Model users are able to quantify upper limits for costs of adaptation measures to reduce damages by climate change. For instance, it is possible to evaluate the impact of temperature increases on different sectors and the overall impact on total gross value added, consumption, investment etc. The discounted cumulative difference between a scenario without a temperature increase and with a temperature increase is an approximation of the expected costs.

Our model is implemented in the open-source environment Dynare and can be run using Matlab or Octave[2]. Its open-source environment has the advantage that it increases the number of potential model users to acquire the necessary skills and experience to work with the model. Model parameters are calibrated to match (structural) characteristics of the Vietnamese economy. Sectors in the model correspond to economic activities and the classification by the General Statistics Office of Vietnam (GSO). Regions are based on the statistical regions depicted in Figure 1. It is possible to modify the number of sectors and regions by aggregating the official data. This allows to reduce the size of the model and makes it easier to test new modifications and features of the model. The core of the model can be extended to feature different aspects of the economy.

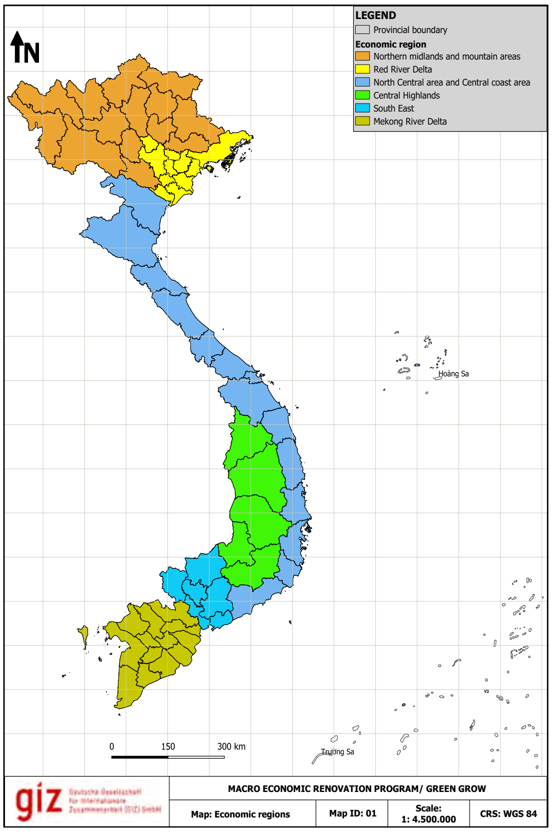
In order to evaluate the costs and benefits associated with adaptation measures given the evolution of different climate variables, we first need to define a *Baseline* scenario. It describes the evolution of the Vietnamese economy under the assumption of no additional climate change. Costs associated with climate change are then defined as the difference between the Baseline path and some alternative scenarios with additional climate change. The model thus can serve as a laboratory for policymakers and researchers to conduct experiments by alternating different climate variables and adaptation measures. As the model is designed to illustrate long-run dynamics, it is not meant to predict bumps in the road, e.g. short-run deviations from long-run trends like the most recent downturn caused by the COVID-19 pandemic. However, it is still possible to include short-run fluctuations by adjusting the short-run path of the Baseline scenario according to recent economic developments.[3]

In Section 2 the derivation of the model equations is explicitly described. In Section 3 the implementation of scenarios is explained. Readers who are interested in directly using the model can skip the model description and can directly proceed with Section G.

[2]The model is mainly developed for Matlab and using the model with Octave might require several adjustments of the code.

[3]One easy way to do this is to use the latest economic forecasts as conducted by, e.g. the International Monetary Fund (IMF) in October 2021 in the World Economic Outlook to account for the recent downturn and the subsequent recovery.

Figure 1: Map of Vietnam



Source: The illustration is based on Boateng (2012).

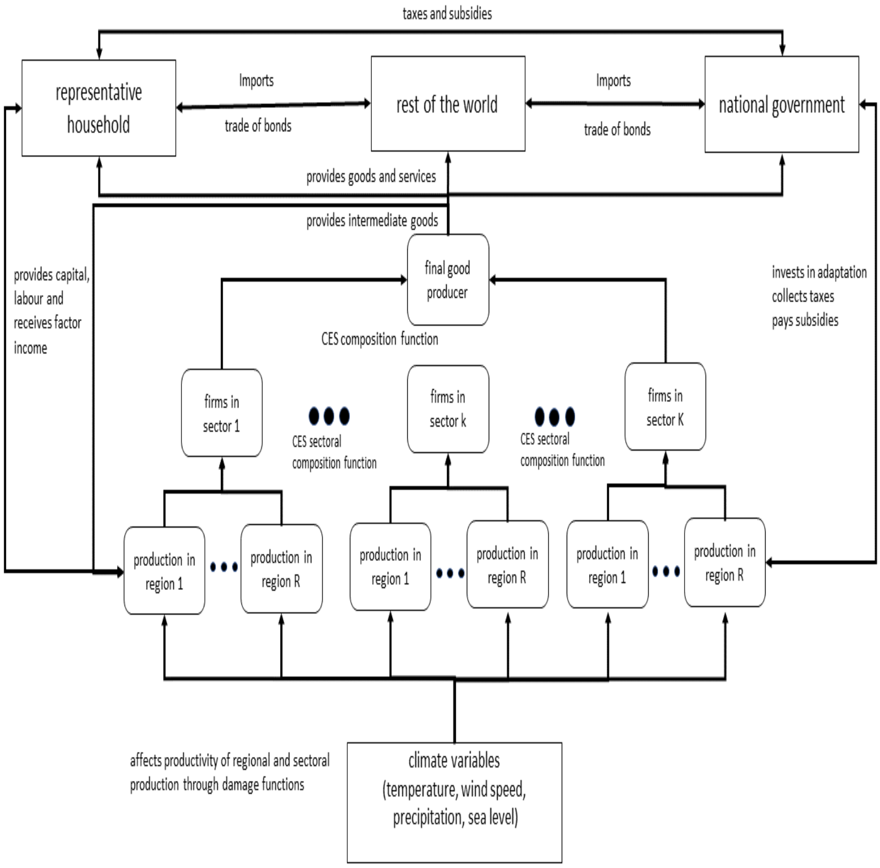
2 Model

In general, the model belongs to the class of neoclassical growth models because no nominal rigidities are explicitly considered. Nevertheless, it is possible to extend the model to feature also nominal rigidities. The model structure is depicted in Figure 2. Regional climate variables (e.g. precipitation, wind speed, temperature and sea level) are exogenous to economic variables. Regional sectoral production functions depend on regional climate variables. The model is meant to reflect small open economies, and hence, the climate system is unaffected by the domestic economic system.

The model consists of an arbitrary number of regions (henceforth denoted by R), aggregate sectors (henceforth denoted by K) and sub-sectors (henceforth denoted by S). Regional differentiation is only provided on the supply side and not on the demand side. Representative households consume goods (henceforth denoted by C), consume housing (henceforth denoted by H), supply capital (henceforth denoted by K) and labour (henceforth denoted by N) to the firms in the regions. Households have access to international capital markets to borrow or lend money by purchasing internationally traded bonds (B). Firms use capital, labour, intermediate goods (henceforth denoted by Q^I) and imports (henceforth denoted by M) to produce goods according to processes that are described by sectoral and region-specific constant elasticity of substitution (CES) production functions. Each sector exports (henceforth denoted by X) a share of its production to the rest of the world.

The government collects taxes (henceforth denoted by τ), consumes (henceforth denoted by G), and can use its funds (henceforth denoted by B^G) to finance adaptation measures (henceforth denoted by G^A) for specific regions and sectors. The link between government expenditure for adaptation purposes

Figure 2: Model structure



Source: own exhibition.

and the reduction in realised damage is integrated through exogenous variables. This allows for any functional relationship between adaptation measures and their effectiveness at the cost of lower transparency compared to a functional form.

Table 28 provides a comprehensive list of all variables and parameters. Appendix C reports all equations of the model.

2.1 Climate variables

In order to capture the effect of climate change on the economy it is necessary to include climate variables into the model. By definition, a small open economy model does not need to include the impact of domestic economic activity on climate variables. Therefore, in contrast to Nordhaus (1993), the model does not include the interaction between economic activity and climate change. Climate variables are independent of other endogenous variables in the model. We model different climate variables by regions based on the simulation results of regional average annual temperature ($tas_{r,t}$), the average precipitation ($pr_{r,t}$), sunshine influx ($sunshine_{r,t}$), relative surface humidity ($hurs_{r,t}$), the average annual wind speed ($SfcWind_{r,t}$), heatwaves ($heatwave_{r,t}$), maximum consecutive dry days ($maxdrydays_{r,t}$), maximum consecutive wet days ($maxwetdays_{r,t}$), storms ($storm_{r,t}$), floods ($floods_{r,t}$), fire ($fire_{r,t}$), landslide

($landslide_{r,t}$) and sea level (SL_t).

$$tas_{r,t} = tas_{0,r} + \eta_{tas_{r,t}} \quad (1)$$
$$SfcWind_{r,t} = SfcWind_{0,r} + \eta_{SfcWind_{r,t}} \quad (2)$$
$$pr_{r,t} = pr_{r,0} + \eta_{pr_{r,t}} \quad (3)$$
$$sunshine_{r,t} = sunshine_{0,r} + \eta_{sunshine_{r,t}} \quad (4)$$
$$hurs_{r,t} = hurs_{0,r} + \eta_{hurs_{r,t}} \quad (5)$$
$$heatwave_{r,t} = heatwave_{0,r} + \eta_{heatwave_{r,t}} \quad (6)$$
$$maxwetdays_{r,t} = maxwetdays_{0,r} + \eta_{maxwetdays_{r,t}} \quad (7)$$
$$storms_{r,t} = storms_{0,r} + \eta_{storms_{r,t}} \quad (8)$$
$$floods_{r,t} = floods_{0,r} + \eta_{floods_{r,t}} \quad (9)$$
$$fire_{r,t} = fire_{r,t} + \eta_{fire_{r,t}} \quad (10)$$
$$landslide_{r,t} = landslide_{0,r} + \eta_{landslide_{r,t}} \quad (11)$$
$$SL_t = SL_0 + \eta_{SL\,t} \quad (12)$$

The approach in eq. 1 to eq. 12 allows to specify the evolution of climate variables according to the projections by meteorological models (e.g. Stocker et al. 2013).

2.2 Demand

The focus of the model is on the supply side. The demand side is represented by a representative household that is consuming and investing. The household receives income from labour and capital allocated to different sub-sectors and regions.

2.2.1 Households

As depicted in Figure 2, representative households h are providing labour and capital to domestic firms f. Households maximize discounted utility over an infinite horizon by choosing consumption $C_t(h)$, capital $K^H_{k,r,t+1}(h)$, investments $I_{k,r,t}(h)$, labour supplied $N_{s,r,t}(h)$, the $H_{t+1}(h)$ housing stock, investments into the housing stock $I^H_t(h)$ and foreign net wealth $B_{t+1}(h)$ to maximize utility constrained by the budget constraint and the law of motion for sectoral and regional capital. Households can be affected by climate change through damages to the capital stock $D^K_{k,r,t}(h)$ and damages to the housing stock $D^H_t(h)$. Further, households can adapt to climate change through discretionary investments ($I^{A,P,Cost}_t(h)$), allocated to either housing ($I^{A,D^H}_t(h)$) or specific sub-sectors and regions ($I^{A,P}_{s,r,t}(h)$). Adaptation measures might require different sub-sectoral products to be implemented. The parameters $i^{A,P}_s$ and $i^{A,P,H}$ are integers defining the sub-sectoral products used to implement the respective adaptation measure.[4]

$$I^{A,P,Cost}_t(h) = I^{A,P,H,Cost}_t(h) + I^{A,P,Sub,Cost}_t(h), \quad (13)$$

$$I^{A,P,H,Cost}_t(h) = \begin{cases} I^{A,D^H}_t(h)\, P^D_{i^{A,P,H},t} & \text{if } i^{A,P,H} \neq 0 \\ I^{A,D^H}_t(h) & \text{if } i^{A,P,H} = 0 \end{cases}, \quad (14)$$

$$I^{A,P,Sub,Cost}_t(h) = \sum_s^S \sum_r^R \begin{cases} I^{A,P}_{s,r,t}(h) P^D_{i^{A,P}_s,t} & \text{if } i^{A,P}_s \neq 0 \\ I^{A,P}_{s,r,t}(h) & \text{if } i^{A,P}_s = 0 \end{cases}. \quad (15)$$

Investments into private adaptation capital ($K^{A,P}_{s,r,t}(h)$) are in contrast to investments into private capital stock or the housing stock not derived from a first order condition reflecting optimal behaviour.

$$K^{A,P}_{s,r,t+1} = \begin{cases} \eta^{I^{A,P}}_{s,r,t} \frac{Y_0}{P_0 P^D_{i^{P,A}_s,0}} & \text{if } i^{P,A}_s \neq 0, \\ \eta^{I^{A,P}}_{s,r,t} \frac{Y_0}{P_0} & \text{if } i^{P,A}_s = 0. \end{cases} \quad (16)$$

[4]For instance, adaptation measures in the housing sector require sub-sectoral goods from the construction sector. In case the sub-sector is the seventh sub-sector the parameter $i^{A,P,H}$ is set to seven.

The Lagrangian eq. 17 of the representative household is

$$\begin{aligned}
\mathcal{L}^{HH} = \sum_{t=0}^{\infty} \beta^t \Bigg[&\left(\frac{\left(C_t(h)^{1-\gamma} H_t^{\gamma}\right)^{1-\sigma^C}}{1-\sigma^C} - \sum_{s=1}^{S}\sum_{r=1}^{R} A^N_{s,r,t}\phi^L_{s,r} \frac{N_{s,r,t}(h)^{1+\sigma^L}}{1+\sigma^L} \right) \\
&- \lambda_t(h) \Bigg(P_t C_t(h) \left((1+\tau_t^C\right) + P_t^H H_t(h) \left((1+\tau_t^H\right) + \sum_{k=1}^{K}\sum_{r=1}^{R} P_t I_{k,r,t}(h) + B_{t+1}(h) \\
&- \sum_{s=1}^{S}\sum_{r=1}^{R} \left(1-\tau_t^N\right) W_{s,r,t} N_{s,r,t}(h) - I^{A,P,Cost}(h)_t P_t \\
&- \sum_{k=1}^{K}\sum_{r=1}^{R} P_t K^H_{k,r,t} r_{k,r,t} \left(1-\tau_t^K\right) - \phi_t^B (r_t^f+1) B_t(h) \Bigg) \\
&- \sum_{k=1}^{K}\sum_{r=1}^{R} \lambda_t(h) \omega^I_{k,r,t}(h) \left\{ K^H_{k,r,t+1} - (1-\delta) K^H_{k,r,t} - I_{k,r,t}\Gamma\left(\frac{I_{k,r,t}}{I_{k,r,t-1}}\right) + D^K_{k,r,t}(h) \right\} \\
&- \sum_{k=1}^{K}\sum_{r=1}^{R} \lambda_t(h) \omega^H_t(h) \left\{ H_{t+1} - \left(H_t\left(1-\delta^H\right) + I^H_t - D^H_t(h)\right) \right\} \Bigg]
\end{aligned} \tag{17}$$

Households receive utility by consuming goods and having residential property, where the intertemporal elasticity of consumption is defined by σ^C. The parameter γ reflects the preference for housing or consumption. Disutility from labour is sector and region specific $\phi^L_{s,r}$, the inverse Frisch elasticity σ^L is identical for all sectors and regions. Households spend money either on consumption goods $P_t\, C_t(h)\,(1+\tau_t^C)$, regional and sector-specific investment $P_{s,r,t} I_{s,r,t}(h)$ or they can save in internationally-traded bonds $B_{t+1}(h) > 0$. It is also possible that domestic households borrow money from international investors $B_{t+1}(h) < 0$. They receive income from labour $W_{s,r,t}\, N_{s,r,t}(h)\,(1-\tau_t^N)$, capital renting $P_{s,r,t}\, r_{s,r,t}\, K^H_{s,r,t}(h)\,(1-\tau_t^K)$ and interest payments on lent money $B_t(h) > 0$ or have to pay interest on borrowed money $B_t(h) < 0$. The first order conditions to the problem are the behavioural equations. Households supply labour according to the FOC w.r.t. labour eq. 18 for each sector and region depending on the wage $W_{s,r,t}$ and the marginal disutility of labour for the specific sector and region

$$\phi^L_{s,r}\, A^N_{s,r,t}\, N_{s,r,t}(h)^{\sigma^L} = \lambda_t(h)\, W_{s,r,t}\,(1-\tau_t^N). \tag{18}$$

Households also decide how much of their income they consume or invest into capital. The capital stock at the end of period t and the beginning of period $t+1$ is predetermined. The Euler equation eq. 19 is obtained by taking the first derivative of the Lagrangian w.r.t. sector and region-specific capital

$$\lambda_{t+1}(h)\,\beta\,\left(P_{t+1}\, r_{k,r,t+1}\,(1-\tau_t^K) + (1-\delta - \sum_{s\in k} D^K_{s,r,t+1})\,\omega^I_{s,r,t+1} \right) = \lambda_t(h)\,\omega^I_{k,r,t}. \tag{19}$$

Households face investment adjustment costs

$$\Gamma(\frac{I_{k,r,t}}{I_{k,r,t-1}}) = 3 - exp\left\{\sqrt{\phi^K/2}\left(\frac{I_{k,r,t}}{I_{k,r,t-1}} - 1\right\}\right) - exp\left\{-\sqrt{\phi^K/2}\left(\frac{I_{k,r,t}}{I_{k,r,t-1}} - 1\right)\right\}, \tag{20}$$

which are sector and region specific. The specification of the investment adjustment cost function is the same as proposed and estimated by Christiano et al. (2014) for the US. The marginal value of sectoral and regional investment $\omega^I_{k,r,t}$ is determined by

$$P_t\,\lambda_t(h) = \lambda_t(h)\,\omega^I_{k,r,t}\,\left(\Gamma(\frac{I_{k,r,t}}{I_{k,r,t-1}}) + \frac{\partial\Gamma(\frac{I_{k,r,t}}{I_{k,r,t-1}})}{\partial(\frac{I_{k,r,t}}{I_{k,r,t-1}})}\,\frac{I_{k,r,t}}{I_{k,r,t-1}}\right) - \beta\lambda_{t+1}(h)\,\omega^I_{k,r,t+1}\,\frac{\partial\Gamma(\frac{I_{k,r,t+1}}{I_{k,r,t}})}{\partial(\frac{I_{k,r,t+1}}{I_{k,r,t}})}\,\left(\frac{I_{k,r,t+1}}{I_{k,r,t}}\right)^2. \tag{21}$$

Households decide how much they spend on consumption or investments in the housing stock. The FOC of households with respect to consumption is

$$\lambda_t(h)\, P_t\, (1+\tau_t^C) = (1-\gamma) C_t(h)^{-\gamma}\, (H_t(h)^{\gamma} C_t(h)^{1-\gamma})^{-\sigma^C}. \tag{22}$$

Further, they decide about the size of the housing stock $H_{t+1}(h)$ they have at the end of period t and at the beginning of period $t+1$. Therefore, the stock of houses is known in period t and is predetermined. The first order condition of the household with respect to housing is

$$\begin{aligned}\lambda_t(h)\, {\omega^H}_t(h) = \beta\, \Bigg(& \left(1-\delta^H\right)\, (\mathbb{E}_t \lambda_{t+1}(h))\, \left(\mathbb{E}_t \omega^H_{t+1}(h)\right) \\ & + \gamma\, (\mathbb{E}_t C_{t+1}(h))^{1-\gamma}\, H_{t+1}(h)^{\gamma-1}\, \left(\mathbb{E}_t C_{t+1}(h)^{1-\gamma}\, (H_{t+1}(h))^{\gamma}\right)^{-\sigma^C} \Bigg)\end{aligned} \tag{23}$$

The first order condition with respect to investment in the housing stock is

$$\lambda_t(h)\, {\omega^H}_t = \lambda_t(h)\, {P^H}_t\, \left(1 + {\tau^C}_t\right) \tag{24}$$

2.2.2 Government

We are interested in different policy measures taken by the government to adapt to a new climate regime. Government behaviour is not a result of an optimization problem. The government collects taxes from consumption $\tau_t^C\, C_t$, labour income $\sum_k^K \sum_r^R (\tau_t^N + \tau_{s,r,t}^{N,F})\, W_{s,r,t}\, N_{s,r,t}\, Pop_t$ and capital income $\sum_k^K \sum_r^R (\tau^K + \tau_{r,s,t}^K)\, P_{s,r,t}\, r_{s,r,t}\, K_{s,r,t}$. In order to finance its activities the government can borrow loans from the rest of the world $B_{t+1}^G < 0$ and has to repay loans and interest from the previous period denominated in foreign currency $(1 + r_t^f)$ identical to the interest rates paid by households. The government budget constraint boils down to eq. 25.

$$\begin{aligned}G_t + G_t^{A,Cost} + B_{t+1}^G = & \sum_s^S \sum_r^R \left\{ (\tau_t^K + \tau_{r,s,t}^{K,F})\, P_{s,r,t}\, r_{s,r,t}\, K_{s,r,t} + (\tau_t^N + \tau_{s,r,t}^{N,F})\, W_{s,r,t}\, N_{s,r,t}\, Pop_t \right\} \\ & + (1 + r_t^f)\, S_t^f\, \phi_t^B\, B_t^G\end{aligned} \tag{25}$$

$$G_t^{A,Cost} = G_t^{A,H}\, P^D_{i^{G,H},t} + \sum_s^S \begin{cases} \sum_r^R G^A_{s,r,t} P^D_{i_s^{G,A},t} & \text{if } i_s^{G,A} \neq 0 \\ \sum_r^R G^A_{s,r,t} & \text{if } i_s^{G,A} = 0 \end{cases} \tag{26}$$

Government expenditures can be used to finance adaptation measures $G_t^{A,Cost}$ in specific sectors and regions $G^A_{s,r,t}$ against climate change. In addition, the government can directly invest in adaptation measures for the construction sector $G_t^{A,H}$ to avoid the destruction of houses owned by households. Parameters $i_s^{G,A} \in (1,\ldots,S)$ and $i^{G,H} \in (1,\ldots,S)$ specify the adaptation expenditures from a specific sub-sector. The effectiveness of adaptation measures might also depend on previous expenditures of the government. Therefore, we consider capital stocks $K^A_{s,r,t+1}$ financed by expenditures on adaptation measures. The depreciation rate $\delta_{K^A,s,r}$ defines necessary maintenance costs, which are assumed to be proportional to the capital stock.

Government expenditures on adaptation measures, taxes on regional and sectoral capital expenditure, and government debt are independent of other variables, or to formulate it differently are discretionary. This allows us to evaluate different policy paths for the future and to model the variables by exogenous processes as stated in eq. 27.

$$
\begin{aligned}
K^A_{s,r,t+1} &= \begin{cases} \eta^A_{s,r,t} \frac{Y_0}{P_0 P^D_{i^{G,A}_s,0}} & \text{if } i^{G,A}_s \neq 0 \\ \eta^A_{s,r,t} \frac{Y_0}{P_0} & \text{if } i^{G,A}_s = 0 \end{cases} \\
K^A_{s,r,t+1} &= (1 - \delta_{K^A,s,r})\, K^A_{s,r,t} + G^A_{s,r,t} \\
\tau^{K,F}_{s,r,t} &= \tau^{K,F}_{s,r,0} + \eta^{\tau^{K,F}}_{s,r,t} \\
\tau^{N,F}_{s,r,t} &= \tau^{N,F}_{s,r,0} + \eta^{\tau^{N,F}}_{s,r,t} \\
\tau^K_t &= \tau^K_0 + \eta^{\tau^K}_t \\
\tau^N_t &= \tau^N_0 + \eta^{\tau^N}_t \\
\tau^H_t &= \tau^H_0 + \eta^{\tau^H}_t \\
B^G_{t+1} &= B^G_0 + \eta^{B^G}_t
\end{aligned} \tag{27}
$$

2.2.3 Access to international financial markets

Households have access to the international financial market to purchase and sell internationally-traded bonds. However, we only consider net foreign positions.

$$
\lambda_{t+1}\, \beta\, \phi^B_{t+1} \left(1 + {r^f}_{t+1}\right) = \lambda_t \tag{28}
$$

with the world interest rate r^f. The required interest rate is above the world interest rate if the foreign debt ($B_{t+1} < 0$)/ foreign claims ($B_{t+1} > 0$) relative to GDP increases/decreases and future net exports relative to GDP will decrease.

$$
\phi^B_{t+1} = exp\left(-\phi^B\, (r^f_{t+1} \frac{B_{t+1} + B^G_{t+1}}{Y_{t+1}} + \frac{NX_{t+1}}{Y_{t+1}})\right) \tag{29}
$$

We introduce ϕ^B_{t+1} to ensure stability of the system as discussed in Schmitt-Grohé & Uribe (2003).

2.3 Production

A company operating under perfect competition provides domestically used goods Q^U_t as a combination of domestically produced and used goods Q^D_t and imported goods M_t. Imports and domestically produced and used products are combined according to a constant elasticity of substitution production function with distributional parameter ω^F and elasticity of substitution η^F. Domestically produced and used goods Q^D_t are an aggregate of sectoral products $Q^A_{k,t}$ according to a constant elasticity of substitution (CES) production function with distribution parameters $\omega^{Q^A}_k$ and the elasticity of substitution between different sectors η^Q. Similar is the procedure for imports, where sub-sectoral imports $M_{s,t}$ are aggregated according to a CES production function with distribution parameters ω^M_s and elasticity of substitution parameter η^M. Sectoral aggregate products are aggregated using sub-sectoral products $Q^D_{s,t}$. The domestically used sub-sectoral products and exports $X_{s,t}$ are aggregated according to a CES production function from regional sub-sectoral production $Q_{s,r,t}$ with distribution parameters $\omega^Q_{r,s}$ and elasticity of substitution for products from different regions in one sub-sector η^Q_s according to a CES production function.

$$\max_{Q_{s,r,t},M_{s,t}} P_t Q_t^U - \sum_{s,r} P_{s,r,t}^D Q_{s,r,t}^D - \sum_s P_{s,t}^M M_{s,t} \tag{30}$$

$$\text{where } Q_t^U = \left({\omega^F}^{\frac{1}{\eta^F}} {M_t}^{\frac{\eta^F-1}{\eta^F}} + (1-\omega^F)^{\frac{1}{\eta^F}} {Q_t^D}^{\frac{\eta^F-1}{\eta^F}} \right)^{\frac{\eta^F}{\eta^F-1}} \tag{31}$$

$$M_t = \left(\sum_s^S {\omega_s^M}^{\frac{1}{\eta^M}} {M_{s,t}}^{\frac{\eta^M-1}{\eta^M}} \right)^{\frac{\eta^M}{\eta^M-1}} \tag{32}$$

$$Q_t^D = \left(\sum_k^K {\omega_k^{Q^A}}^{\frac{1}{\eta^Q}} {Q_{k,t}^{A,D}}^{\frac{\eta^Q-1}{\eta^Q}} \right)^{\frac{\eta^Q}{\eta^Q-1}} \tag{33}$$

$$Q_{k,t}^A = \left(\sum_s^S {\omega_s^Q}^{\frac{1}{\eta_k^Q}} {Q_{s,t}^D}^{\frac{\eta^Q k-1}{\eta_k^Q}} \right)^{\frac{\eta_k^Q}{\eta_k^Q-1}} \tag{34}$$

$$Q_{s,t}^D + X_{s,t} + E_{s,t}^{A,D} P_t = Q_{s,t} = \left(\sum_r^R {\omega_{r,s}^Q}^{\frac{1}{\eta_s^Q}} {Q_{s,r,t}}^{\frac{\eta_s^Q-1}{\eta_s^Q}} \right)^{\frac{\eta_s^Q}{\eta_s^Q-1}} \tag{35}$$

$$X_{s,t} = (D_s^X + \eta_{s,t}^X) \left(\frac{P_{s,t}^D}{P_{s,t}^M} \right)^{-\eta^X} . \tag{36}$$

It is important to note that exports are assumed to increase/decrease with a decrease/increase in the relative domestic price to the import price of the specific sector. The time-invariant exogenous demand for exports D_s^X can be adjusted through the exogenous export shock $\eta_{s,t}^X$. In addition to exports sub-sectoral output can be used to implement adaptation measures the additional demand for the respective sub-sector is the sum of private and public adaptation expenditures into housing and sub-sectoral adaptation demand

$$E_{s,t}^{A,D} = 1(i^{G,H} = s) G_t^{A,H} + \sum_m^S \sum_r^R G_{m,r,t}^A 1(i_m^{G,A} = s) + 1(i^{P,H} = s) I_t^{A,H} + \sum_m^S \sum_r^R I_{m,r,t}^{A,P} 1(i_m^{A,P} = s). \tag{37}$$

We can use the envelope theorem to derive the following first-order condition with respect to products $Q_{s,r,t}$ produced in sub-sector s in region r:

$$\begin{aligned}
P_t \frac{\partial Q_t^U}{\partial Q_t^D} \frac{\partial Q_t^D}{\partial Q_{k,t}^A} \frac{\partial Q_{k,t}^A}{\partial Q_t^D} \frac{\partial Q_{s,t}^D}{\partial Q_{k,t}^A} \frac{\partial Q_{s,t}^D}{\partial Q_{s,r,t}^D} &= P_{s,r,t}^D \\
P_t (1-\omega^F) \left(\frac{Q_t^D}{Q_t^U} \right)^{-\frac{1}{\eta^F}} &= P_t^D && (38) \\
\omega_k^{Q^A} \left(\frac{Q_{k,t}^A}{Q_t^D} \right)^{-\frac{1}{\eta^Q}} &= \frac{P_{k,t}^A}{P_t^D} && (39) \\
\omega_s^{Q^D} \left(\frac{Q_{s,t}}{Q_{k,t}^A} \right)^{-\frac{1}{\eta_k^{Q^A}}} &= \frac{P_{s,t}^D}{P_{k,t}^A} && (40) \\
\omega_{s,r}^{Q^D} \left(\frac{Q_{s,r,t}}{Q_{s,t}} \right)^{-\frac{1}{\eta_s^{Q^D}}} &= P_{s,r,t}^D && (41)
\end{aligned}$$

For readability, the model features for each marginal product a relative price. At the regional and sectoral level, representative firms are maximizing profits using capital $K_{s,r,t}$ and labour $L_{s,r,t} = N_{s,r,t}\, Pop_t$

provided by households to produce products. They charge a price $P^D_{s,r,t}$ for their products and have to pay households wages $W_{s,r,t}$, interest on rented capital $P_{s,r,t}\, r_{k,r,t}$, taxes related to the wage bill $\tau^{N,F}_{s,r,t}$ and on capital expenditure $\tau^{K,F}_{s,r,t}$. Representative firms have access to a regional and sector specific constant elasticity of substitution production function. The productivity of capital and labour of a firm in one sector and region depends on the climate variables, and the adaption measures by the government represented by a damage function affecting total factor productivity $A_{s,r,t}$ by $D_{s,r,t}$. Further, we also consider climate induced damages affecting labour productivity $D_{N,s,r,t}$. In contrast to Nordhaus (1993), we assume no explicit functional form of the damage functions (eq. 42–44).

$$D_{s,r,t} = \eta^{D}_{s,r,t}. \tag{42}$$

$$D^N_{s,r,t} = \eta^{D^N}_{s,r,t}. \tag{43}$$

$$D^K_{s,r,t} = \eta^{D^K}_{s,r,t}. \tag{44}$$

Firms in each region and sector have access to a constant elasticity of substitution production function with production factors labour, capital and intermediate products. Eq. 45 states the optimization problem of the firm.

$$\begin{aligned}
&\underset{Q^I_{s,r,t},N_{s,r,t},K_{s,r,t}}{max} \; P_{s,r,t}\, Q_{s,r,t} - W_{s,r,t}\, N_{s,r,t}\, Pop_t\, (1+\tau^{N,F}_{s,r,t}) - r_{s,r,t}\, P_{s,r,t}\, K_{s,r,t}\, (1+\tau^{K,F}_{s,r,t}) - P_t\, Q^I_{s,r,t} \\
&\text{s.t. } Y_{s,r,t} = A_{s,r,t}(1-D_{s,r,t}) \left[{\alpha^N_{s,r}}^{\frac{1}{\eta^{NK}_{s,r}}} \left(A^N_{s,r,t}\,(1-D^N_{s,r,t})\, Pop_t\, N_{s,r,t}\right)^{\rho_{s,r}} + {\alpha^K_{s,r}}^{\frac{1}{\eta^{NK}_{s,r}}} \left(K_{s,r,t}\right)^{\rho_{s,r}} \right]^{\frac{1}{\rho_{s,r}}}, \\
&\qquad \text{where } \rho_{s,r} = \frac{\eta^{NK}_{s,r}-1}{\eta^{NK}_{s,r}}.
\end{aligned} \tag{45}$$

$$Q_{s,r,t} = \left[{\omega^I_{s,r}}^{\frac{1}{\eta^I_s}} \left(Q^I_{s,r,t}\right)^{\rho^I_s} + (1-\omega^I_{s,r})^{\frac{1}{\eta^I_s}} \left(Y_{s,r,t}\right)^{\rho^I_s} \right]^{\frac{1}{\rho^I_s}}, \quad \text{where } \rho^I_s = \frac{\eta^I_s - 1}{\eta^I_s}. \tag{46}$$

Demand for production factors is given by the first-order condition of the above optimisation problem. The Lagrange multiplier is equal to the price charged by companies.

$$\begin{aligned}
\frac{W_{s,r,t}}{P_{s,r,t}}\,(1+\tau^{N,F}_{s,r,t}) &= {\alpha^N_{s,r}}^{\frac{1}{\eta^{NK}_{s,r}}} \left(A_{s,r,t}\,(1-D_{s,r,t})\, A^N_{s,r,t}\,(1-D^N_{s,r,t})\right)^{\rho_{s,r}} \left(\frac{Pop_t N_{s,r,t}}{Y_{s,r,t}}\right)^{-\frac{1}{\eta^{NK}_{s,r}}} \\
r_{s,r,t}\,(1+\tau^{K,F}_{s,r,t}) &= {\alpha^K_{s,r}}^{\frac{1}{\eta^{NK}_{s,r}}} \left(A_{s,r,t}\,(1-D_{s,r,t})\right)^{\rho_{s,r}} \left(\frac{K_{s,r,t}}{Y_{s,r,t}}\right)^{-\frac{1}{\eta^{NK}_{s,r}}} \\
\frac{P_t}{P^D_{s,r,t}} &= {\omega^{Q^I}_{s,r}}^{\frac{1}{\eta^I_s}} \left(\frac{Q^I_{s,r,t}}{Q_{s,r,t}}\right)^{-\frac{1}{\eta^I_s}} \\
\frac{P_{s,r,t}}{P^D_{s,r,t}} &= (1-\omega^{Q^I}_{s,r})^{\frac{1}{\eta^I_s}} \left(\frac{Y_{s,r,t}}{Q_{s,r,t}}\right)^{-\frac{1}{\eta^I_s}}
\end{aligned} \tag{47}$$

We use the more general case of the CES production function rather than the more commonly used Cobb-Douglas production function. The parameter $\eta^{NK}_{s,r}$ allows us to control the response of capital and labour demand to temporary productivity shocks. Temporary productivity shocks are in our setup also weather extremes. Cyclones can destroy the capital stock. Firms can either substitute capital using more labour in the period, e.g. using more labour to replace tractors. Or they need to lay off workers because they are useless without machines, e.g. destruction of factories. The parameter $\eta^{NK}_{s,r}$ allows specifying the reaction of firms.

2.3.1 Resource constraint

Households and governments use final domestic goods (denoted by Q_t) produced by firms fewer intermediates goods Q_t^I for consumption, investment, and for exports (denoted by X_t), and can also use imports M_t for consumption and investment. This gives rise to the well-known resource constraint or the expenditure approach to define GDP.

$$P_t^D\, Q_t = P_t\,(Q_t^I + \overbrace{C_t+I_t+G_t+I_t^{A,P,Cost}+G_t^{A,H}+\sum_s \sum_r G^A_{s,r,t} + \underbrace{NX_t}_{P_t^D X_t - P_t^M M_t}}^{Y_t}) \tag{48}$$

The aggregation of the budget constraints of the representative households also states that positive net exports are used to increase net financial wealth to the rest of the world.

$$NX_t = B_{t+1} + B_{t+1}^G - (1 + r_t^f)\phi_t^B (B_t + B_t^G) \tag{49}$$

Correia et al. (1995) provide a more detailed discussion of the derived equations.

2.4 Rest of the world

The demand for domestic exports and foreign imports is not explicitly modelled in this version of the model. Net exports are total expenditures for imports less total revenue from exports. The trade balance depends on the demand for subsectoral imports and the supply for sub-sectoral exports. Demand for sub-sectoral imports grows with the overall production level in the economy and the price of imports relative to domestic products. Exports depend on the terms of trade defined as the domestic and imported price level. The world interest rate r_t^f determines how much governments and households have to pay back in domestic currency as net lenders or how much they receive as a net borrower from the rest of the world. Here the world interest rate is independent of domestic developments, and only the effective exchange rate adjusts according to eq. 28.

$$NX_t = P_t^D X_t - P_t^M M_t \tag{50}$$

$$P_{s,t}^M = P_{s,0}^M + \eta_{s,t}^{P^M} \tag{51}$$

$$X_{s,t} = (D_s^X + \eta_{s,t}^X) \left(\frac{P_{s,t}^D}{P_{s,t}^M} \right)^{-\eta^X} . \tag{52}$$

Import prices $P_{s,t}^M$ for different sub-sector goods are exogenous and do not respond to endogenous variables. Sub-sector exports are a share of sub-sector production and react to the terms of trade in the sub-sector.

3 Scenario Analysis at the Sectoral Level

For simulations, it is necessary to specify a direct mapping between sectors in the model and the available data. The analysis in the following paragraphs will differentiate between five aggregate sectors and 17 sub-sectors. The specific mapping is reported in Table 20. We use this mapping to reduce the number of state variables in the model. Capital stocks for each aggregate sector are simulated. This implicitly assumes that the capital stock in the aggregate sector can be used in the different sub-sectors. However, the model can also use each sub-sector as an individual sector. Nevertheless, this also allows specifying different substitutability across the sub-sectors. For instance, the capital stock in the service and health sector can be used in both sub-sectors (e.g. computers, cars and beds).

3.1 Calibration

Before we can conduct scenario analysis we need to calibrate the model to reflect the current situation of the Vietnamese economy. We make use of an extended input-output table to reflect the economic structure for the year 2014. We calibrate the production function parameters $\alpha^K_{s,r}$, $\alpha^N_{s,r}$ such that we match for a given elasticity of substitution $\eta^{NK}_{s,r}$ the observed share of the wage bill on gross value added $\frac{W_{s,r,0}\,N_{s,r,0}}{P_{s,r,0}\,Y_{s,r,0}}$ and ensure a correct accounting of factor income by economic activity. Further, we calibrate the sectoral composition production function parameters $\omega^Q_{s,r}$, ω^Q_s, $\omega^{Q^A}_k$ for a given elasticity of substitution η^Q_s, $\eta^{Q^A}_k$, η^Q to meet the initial gross value added shares $\phi^Y_{s,r,0} = \frac{P_{s,r,0}\,Y_{s,r,0}}{P_0\,Y_0}$ for the year 2014. We further know the share of intermediate products $\frac{P\,Q^I_s}{P^D_s\,Q_s}$ in each sub-sector and assume identical sub-sectoral shares in each region.[5]. We further need to specify how labour supply responds to wage changes. Therefore, we need to specify the value for the inverse Frisch elasticity (σ^L). We take the value 0.5 from Nguyen (2020). Further, the intertemporal elasticity of substitution of consumption is set to $\sigma^C = 1$. The capital stock depreciation rate (δ) is identical across sectors and regions and equals 0.045.[6] We model a very simplified tax system in Vietnam. All tax revenues of the government come from a tax on consumption in the model. The tax rate τ^C_0 is set to 20 %. This is the relation between total tax income and consumption in Vietnam in the year 2014. There are adjustment costs for the capital stock and for foreign assets. We calibrate the curvature of the adjustment cost functions to be 10 with the parameters ϕ^K and ϕ^B. The discount factor β is equal to 0.9606 and ensures an initial ratio between investment and gross value added of approximately 23 %.

For the production functions, it is necessary to assign values for the elasticity of substitution parameters between capital and labour ($\eta^{NK}_{s,r}$), sub-sectoral products for different regions η^Q_s, sub-sectoral products belonging to one sector $\eta^{Q^A}_k$, between sectoral products η^Q and between imports and domestically produced products η^F. We assume a Cobb-Douglas production function for the creation of gross value added from labour and capital ($\eta^{NK}_{s,r} = 1 \forall s, r$). The elasticity of substitution between intermediate inputs and gross value added is set to $\eta^I_{s,r} = 1.01$ and reflects a quasi Cobb-Douglas production function. For the elasticity of substitution between different regions in one sub-sector η^Q_s we distinguish between sub-sectors primarily producing tradable ($eta^Q_s = 10$) or non-tradable goods and services ($eta^Q_s = 0.01$). Table 1 reports the elasticity of substitution parameters for each sub-sector. We test the elasticity of substitution between different sub-sectors belonging to one aggregate sector k to be equal to $\eta^{Q^A}_k = 0.01$. Therefore, we estimate the elasticity of substitution between the different sub-sectors in one sector k and use a t-test whether we can reject the null hypothesis of $\eta^{Q^A}_k = 0.01$. We can not reject the null hypothesis for any of the sectors (see Appendix F). The same procedure is applied for the elasticity of substitution between different aggregate sectors η^Q. The elasticity of substitution between foreign and domestic products is calibrated to $\eta^F = 1.83$ and the export price elasticity is set to $\eta^X = 0.83$ (see Christiansen et al. 2011, in Table 6.1 and 6.2 last column reported for Vietnam).

In the initial steady state population is set to $PoP_0 = 0.9171385$ and reflects 91,713.850 persons in Vietnam.[7] Further, we set the initial nominal GDP to $P_0\,Y_0 = 1.86$ and reflects a GDP value of 186 billion Dollars.[8]. In 2014, the average weekly hours worked was 43.5[9] of 168 potential hours. In 2014 52,744,000 persons have been employed.[10] The initial share of hours worked is $N_0 = \frac{43.5}{168}\frac{52{,}744{,}00}{90{,}728{,}000} \approx 0.15$. In 2014, the average housing area in Vietnam was $\frac{H_0}{PoP_0} = 23\frac{m^2}{Person}$.[11] Investments into the housing stock relative to GDP are set to 0.5 %. Investments in the housing stock are expenditures by households for residential buildings.

Table 2 reports the export and intermediate product shares relative to the revenue of the specific sector. They are computed by aggregating all exports and intermediate products used by the respective commodities and industry categories belonging to the sector and dividing them by aggregated total sub-sectoral output. Import shares, in contrast, are expressed as a share of total national imports.

Subsectoral import and export shares define the ratio of net exports to GDP. Further, net exports define the net foreign asset position of the domestic households to the rest of the world. Therefore, the foreign debt level is computed endogenously and can be evaluated against empirical data. In addition

[5] Appendix E reports the procedure in more detail.
[6] The value for the depreciation rate is reported in IMF country report No. 18/216.
[7] Source: General Statistical Office of Vietnam Table E02.01
[8] Source: https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=VN
[9] Source: https://www.ceicdata.com/en/vietnam/average-working-hour-per-week
[10] Source: General Statistical Office of Vietnam Table E02.01
[11] Source: https://vietnamnews.vn/society/349388/vns-average-floor-area-per-person-is-228sqm.html

Table 1: Sub-sectoral elasticity of substitution

Rice	10
Other annual crops	10
Fruit tree	10
Dry rubber	10
Coffee	10
Other perennial crops	10
Live stock and agricultural services	10
Aquaculture	10
Forestry	10
Water	0.01
Energy	10
Manufacturing	10
Construction	0.01
TransportWater	0.01
TransportLand	0.01
Health	0.01
Services	0.01

Source: own computation.

Table 2: Sub-sectoral exports and intermediate product shares

Sector	Export share $(\phi_s^X = \frac{X_s}{Q_s})$	Import shares $(\phi_s^M = \frac{P_s^M M_s}{P^M M})$	intermediate products $(\phi_s^{Q^I} = \frac{P Q_s^I}{P_s^D Q_s})$
Rice	0.001	0.001	0.559
Other anuual crops	0.036	0.018	0.557
Fruit tree	0.143	0.001	0.640
Dry rubber	0.770	0.008	0.415
Coffee	0.350	0.001	0.568
Other perennial crops	0.387	0.009	0.473
Live stock and agricultural services	0.009	0.003	0.813
Aquaculture	0.130	0.001	0.711
Forestry	0.142	0.048	0.553
Water	0.001	0.001	0.530
Energy	0.345	0.030	0.579
Manufacturing	0.338	0.817	0.820
Construction	0.001	0.001	0.759
Transport Water	0.244	0.001	0.796
Transport Land	0.218	0.003	0.698
Health	0.052	0.003	0.595
Services	0.140	0.054	0.562

Source: National expert's extended IO table and own computation.

to the above-mentioned shares, it is also necessary to have data on regional and sub-sectoral gross value added, employment and labour cost shares. So far, we only have access to national shares reported in Table 3. Therefore it is necessary to approximate the contribution of each region to each sector. For the

Table 3: Value added, employment and labour cost shares

Sector	VA shares ($\phi_s^Y = \frac{P_s Y_s}{P Y}$)	Employment shares ($\phi_s^N = \frac{N_s}{N}$)	LC shares ($\phi_s^W = \frac{W_s N_s}{P Y}$)
Rice	0.0349	0.1009	0.4950
Other annual crops	0.0289	0.0835	0.4995
Fruit Tree	0.0068	0.0196	0.4869
Dry rubber	0.0097	0.0279	0.6137
Coffee	0.0084	0.0242	0.5542
Other perennial crops	0.0059	0.0170	0.3490
Livestock and other agricultural products	0.0203	0.0587	0.4767
Aquaculture	0.0295	0.0854	0.5262
Forestry	0.0158	0.0457	0.5840
Water	0.0027	0.0021	0.3571
Energy	0.0960	0.0074	0.2304
Manufacturing	0.3205	0.1406	0.4817
Construction	0.0490	0.0628	0.7243
Transport Water	0.0039	0.0041	0.3838
Transport Land	0.0238	0.0250	0.4526
Health	0.0144	0.0093	0.6911
Services	0.3296	0.2859	0.5441

Source: National expert's extended IO table, GSO and own computation.

sub-sector rice, the regional share of the national production of paddy in the year 2014 is considered.[12]. Regional shares for other annual crops, fruit trees, dry rubber, other perennial crops, livestock and other agricultural products is the share of farms for cultivation.[13]. The regional shares of coffee reflect the share of production by statistical region in 2014.[14] For the aquaculture sector regional production shares in 2014 are used.[15] Regional shares for the forestry sector reflect the regional share of wood production in 2014.[16] Regional shares for the construction sector refelct the share of completed housing area by region.[17]. Manufacturing and transport shares represent the labour force shares in 2014.[18], For water, energy, health and services population shares are used.[19] The shares are reported in Table 4.

Further, we need to specify initial values for the different climate variables. They are the respective averages across provinces for each region for the year 2015, except for sunshine hours (we sum over all provinces). All initial values are reported in Table 19.

3.2 Baseline

For the Baseline scenario, we assume no impact on climate change on the economy. Further, we compute sectoral productivities $A_{s,r,t}$ to match the reported sectoral growth rates $\frac{P_{s,r,t} Y_{s,r,t}}{P_{s,r,t-1} Y_{s,r,t-1}}$ from Figure 15. The same is true for labour specific productivity shocks $A^N_{s,r,t}$ to match growth rates for labour supply shares $\frac{\frac{N_{s,r,t}}{N_t}}{\frac{N_{s,r,t-1}}{N_{t-1}}}$. The Vietnamese population is growing at an exogenous rate, according to projections

[12]Source: General Statistical Office of Vietnam Table E06.15
[13]Source: General Statistical Office of Vietnam Table E06.02
[14]Source: Vietnam Coffee Cocoa Association `http://www.vicofa.org.vn/country-coffee-profile-vietnam-bid385.html`.
[15]Source: General Statistical Office of Vietnam Table E06.56
[16]Source: General Statistical Office of Vietnam Table E06.45
[17]Source: General Statistical Office of Vietnam Table E04.22
[18]Source: General Statistical Office of Vietnam Table E02.34
[19]Source: General Statistical Office of Vietnam Table E02.01

Table 4: Regional shares for value added and employment shares

Region	Red River Delta	Northern Midland and Mountain area	Northen Central and Central Coastal Area	Central Highlands	Southeast	Mekong River Delta
Rice	0.1503	0.0743	0.1564	0.0277	0.0300	0.5613
Other annual crops	0.2260	0.0540	0.1070	0.1080	0.2250	0.2803
Fruit Tree	0.2260	0.0540	0.1070	0.1080	0.2250	0.2803
Dry rubber	0.2260	0.0540	0.1070	0.1080	0.2250	0.2803
Coffee	0.0100	0.0240	0.0140	0.8720	0.0700	0.0100
Other perennial crops	0.2260	0.0540	0.1070	0.1080	0.2250	0.2803
Livestock and other agricultural products	0.2260	0.0540	0.1070	0.1080	0.2250	0.2803
Aquaculture	0.1620	0.0280	0.0670	0.0080	0.0330	0.7019
Forestry	0.0520	0.2780	0.5000	0.0600	0.0430	0.0674
Water	0.2282	0.1286	0.2152	0.0609	0.1740	0.1931
Energy	0.2282	0.1286	0.2152	0.0609	0.1740	0.1931
Manufacturing	0.2270	0.1390	0.2190	0.0610	0.1660	0.1880
Construction	0.2410	0.1410	0.2120	0.0660	0.1250	0.2149
Transport Water	0.2270	0.1390	0.2190	0.0610	0.1660	0.1880
Transport Land	0.2270	0.1390	0.2190	0.0610	0.1660	0.1880
Health	0.2282	0.1286	0.2152	0.0609	0.1740	0.1931
Services	0.2282	0.1286	0.2152	0.0609	0.1740	0.1931

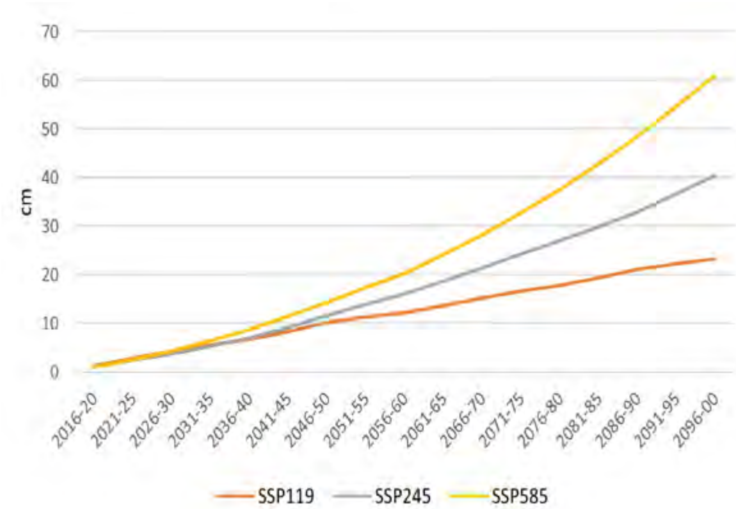
Source: GSO, Vietnam Coffee Cocoa Association and own computation.

by the General Statistical Office (GSO). The projection is depicted in Figure 18. Further, we assume that the relationship between net exports and GDP ($\frac{NX}{Y}$) is constant at the 2014 level. This is ensured through adjustments in the import price level. The housing stock per capita is constant, and the house price increases as a response to a fixed supply of housing areas.

3.3 Climate Change Scenarios

One of the main hazards to the Vietnamese economy is an increase in the sea level. Projections show that climate change can lead to an increase of the sea level until 2100 by 70 cm (see Figure 3). This implies a higher risk of floods in coastal areas and a higher exposure to cyclones. Further, it might reduce the available land for agriculture and other economic activities.

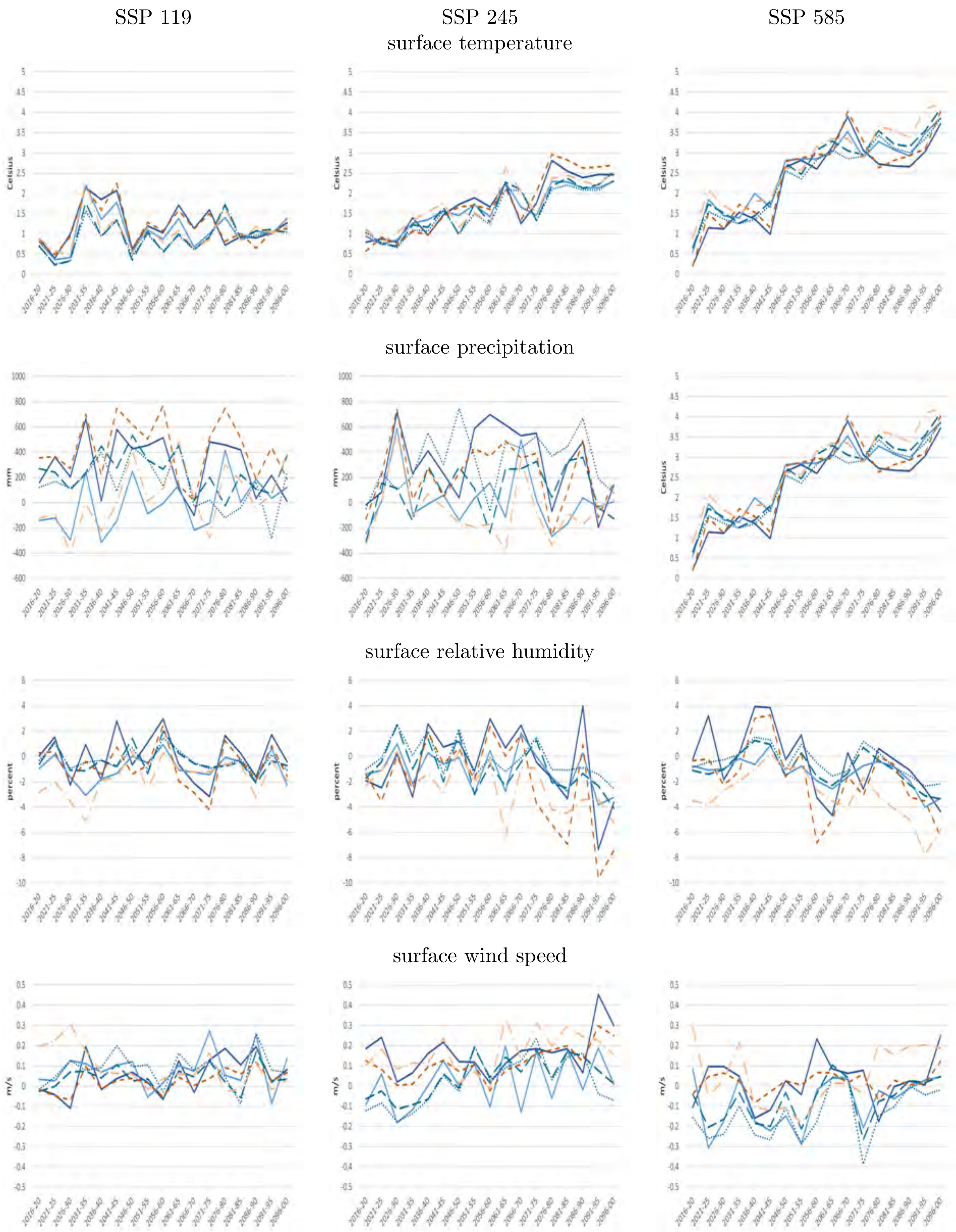
Figure 3: Sea level



Source: Sea-level rise as reported by Masson-Delmotte et al. (2021).

For other climate variables, we use projections by the Meteorological Research Institute (MRI). We explicitly use the simulation results for the shared social path (SSP) scenarios 119, 245 and 585. In order to simulate climate change at a subnational level for the respective regions depicted in Figure 1, we need to aggregate the data from a provincial level to a regional level. Therefore, we use the mapping reported in Table 21. The paths for each climate variable from 2015 to 2100 is depicted in Figure 4 for the considered regions. We can see that the SSP 119 scenario can limit an increase in the surface air temperature to roughly 1°C. The graphs show the change in the respective climate variable to the year 2014. We observe a clear upward trending behaviour of the surface temperature in the SSP 585 scenario. Surface precipitation seems to decline in the SSP 585 scenario.

Figure 4: Simulated change in climate variables



Note: Red River Delta (red), Northern midland and mountain area (gray), Northern Central and Central coastal area (yellow), Central Highlands (blue), South East (green), Mekong River Delta (light blue).
Source: National expert computation based on results from Meteorological Research Institute.

3.3.1 Labour Market

Kjellstrom et al. (2019) estimates that heat stress in Vietnam led to a loss in total working hours by 4.4 percent in 1995. Further, the study also reports the projected loss in working hours of 5.14 percent until 2030 for Vietnam. According to the study the temperature will increase in South-East Asia by 0.8 °C until 2030. The number of working hours lost depends on the respective sector. The more physical intense the labour in a sector is the more working hours are lost (see Table 5). Therefore, employees in sub-sectors demanding heavy physical work outside of buildings will lose more than 5 percent of working hours per one °C. According to the projections by Kjellstrom et al. (2019) and based on own

Table 5: Labour productivity loss

Sub-sector	Description	Physical intensity (W)	Productivity reduction ($D_s^{N,Heat}$ in $\frac{\%}{°C}$)
Rice	Heavy physical work	400	5.71
Other annual crops	Heavy physical work	400	5.71
Fruit Tree	Heavy physical work	400	5.71
Dry rubber	Heavy physical work	400	5.71
Coffee	Heavy physical work	400	5.71
Other perennial crops	Heavy physical work	400	5.71
Livestock and other agricultural products	Heavy physical work	400	5.71
Aquaculture	Heavy physical work	400	5.71
Forestry	Heavy physical work	400	5.71
Water	Moderate physical work	300	2.38
Energy	Moderate physical work	300	2.38
Manufacturing	Moderate physical work	300	2.38
Construction	Heavy physical work	400	5.71
Transport Land	Heavy physical work	400	5.71
Transport Water	Heavy physical work	400	5.71
Health	Clerical/light physical work	200	0.35
Services	Clerical/light physical work	200	0.35

Source: Kjellstrom et al. (2019) Table 6.43 and own computation.

computations we define sub-sectoral labour productivity losses due to an increase in the annual average temperature by

$$D_{s,r,t}^{N} = D_s^{N,Heat} tas_{r,t}. \tag{53}$$

Regions with a stronger increase in temperature and a higher share of heavy physical work will be more affected by climate change than other regions.

3.3.2 Loss of capital in manufacturing

Vietnam will be exposed to sea-level rise. Therefore, some of the land currently used for different economic activities might be lost. For the industry in Vietnam land losses will reduce the capital stock of the affected area. In order to estimate the effect of land losses we first compute the current value per area of capital used by the industry. Therefore, we use the land used for non-agricultural production and offices (2799 km^2) in 2018 and the capital of manufacturing of 7372977 billion VND in 2018 to derive a value of capital per square kilometre of 2634 $\frac{billionVND}{km^2}$.[20] Table 6 reports the computed land losses in km^2 for different sea-level rises. Capital losses caused by sea-level rise are given by (54). The loss

Table 6: Land loss in manufacturing

SLR in cm ($ll_b^{SL,Manu}$)	Red River Delta	Northern Midland and Mountain area	Northen Central and Central Coastal Area	Central Highlands	Southeast	Mekong River Delta
0	0.53	0.00	0.53	0.00	0.00	0.63
5	0.77	0.00	0.77	0.00	0.05	1.74
10	1.25	0.00	1.25	0.00	0.11	4.26
15	1.76	0.00	1.76	0.00	0.19	7.93
20	2.18	0.00	2.18	0.00	0.28	18.11
25	2.69	0.00	2.69	0.00	0.37	18.19
30	3.06	0.00	3.06	0.00	0.46	18.27
35	3.45	0.00	3.45	0.00	0.53	18.38
40	4.20	0.00	4.20	0.00	0.65	18.51
45	4.86	0.00	4.86	0.00	0.76	19.15
50	5.43	0.00	5.43	0.00	0.87	19.56
55	6.07	0.00	6.07	0.00	1.01	19.97
60	6.79	0.00	6.79	0.00	1.17	20.54
65	7.51	0.00	7.51	0.00	1.33	21.27
70	8.31	0.00	8.31	0.00	1.51	22.00
75	9.19	0.00	9.19	0.00	1.68	22.43
80	10.48	0.00	10.48	0.00	1.89	23.02
85	11.68	0.00	11.68	0.00	2.12	23.67
90	12.91	0.00	12.91	0.00	2.39	24.21
95	14.36	0.00	14.36	0.00	5.22	25.04

Source: National expert and own computation.

in capital is determined by the value of capital per square kilometre and multiplied by the land loss in square kilometre for the respective sea-level.

$$D_{10,r,t}^{K} = 2634\frac{10^9 VND}{km^2}\sum_{b=2}^{20} ll_b^{SL,Manu} 1(SL_b < SL_t \leq SL_{b+1}) \quad (54)$$

The underlying assumption for this methodology is that the manufacturing capital stock in Vietnam is uniformly distributed across the country. Some sub national regions might have on average a more modern capital stock. In this case the methodology would need to consider this.

[20] Values are from GSO Table E01.02 and E05.16.

3.3.3 Agriculture

The impact of climate change on the agriculture sector depends on the respective agricultural product and production location. Sectoral experts analysed the effects of climate change on crop yields per hectare for rice and coffee in the Mekong River Delta and the Central Highlands. The Central Highlands produce over 80 percent of coffee in Vietnam. On the other side, the Mekong River Delta makes over fifty percent of rice. Therefore, the production of both agricultural products is highly concentrated. There are different attempts to quantify the impact of climate change on crop yields.

Temperature: Zhao et al. (2017) provide a meta-study to investigate the impact of climate change on crop yields in the world. We use these results for the different crops and translate them into direct effects on the Vietnamese economy. Table 7 reports the expected drop in crop yields due to an increase in the average annual temperature. We use available estimates for Vietnam and China. We see that maise is most vulnerable to a rise in the average yearly temperature.

Table 7: Crop yield loss

Crop	Loss ($\%/^{\circ}C$)	Region
wheat	-2.6	China
rice	-3.0	Vietnam
maize	-8.0	China
soybean	-3.1	China

Source: Zhao et al. (2017).

For rice and fruit tree in the Mekong River Delta, the study explicitly reports an estimate for Vietnam. The same is true for coffee in the Central Highlands.

Sea level: In addition to increasing temperature, the sea-level rise will reduce the available land for agricultural activities. To incorporate this effect, we use data on land usage by province. Further, national experts predict the potential loss of land in different categories for different levels of sea-level rise. We compute the share of land loss used for rice production, other annual crops, fruit trees, dry rubber and other perennial crops. The land loss for fruit trees, dry rubber and other perennial crops is identical due to limitations in data availability. For the computation, we use the following steps:

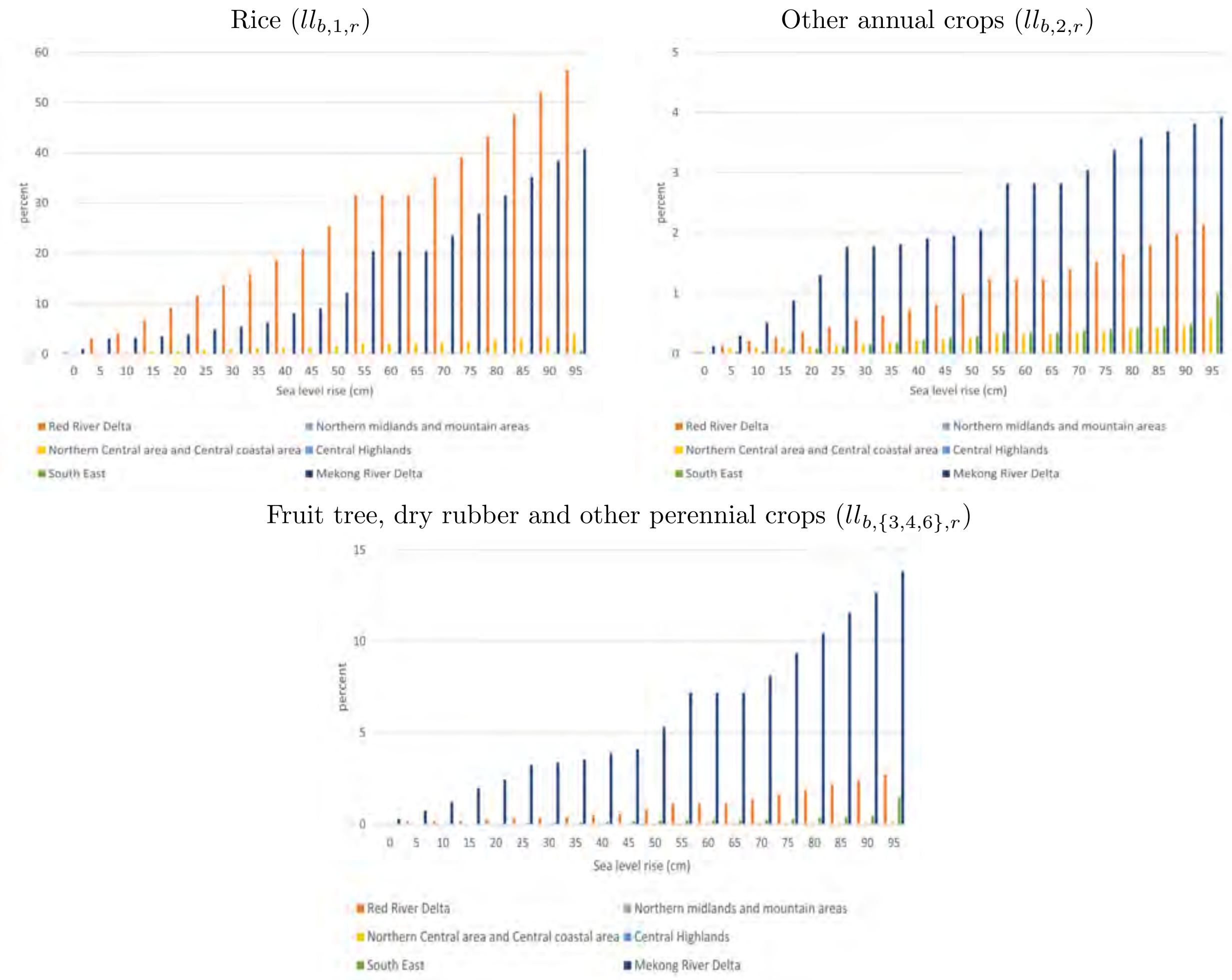
1. First, obtain agricultural production land by province. (Source: GSO Table E01.03)
2. Second, obtain land use by type for Vietnam. (Source: GSO Table E01.02)
3. Create land use by type of agricultural land using the share of regional land used for agricultural production multiplied with the national share of land use by type to get a value for land use by type and region.
4. Compute the share of land loss for the different levels of sea-level rise ($ll_{b,r}$ for $b \in [5(j-1), 5j)$ for $j \in (1, \dots 20)$)

Figure 5 depicts the share of land loss due to different sea-level. The exposure of the two river deltas is the highest. Over 30% of the land currently used for rice might be lost if the sea level rises by 50 cm in the Red River Delta.

The reduction in total factor productivity in the agricultural sector is a linear function in temperature and a non-continuous step function based on indicator functions (1) concerning sea-level rise.

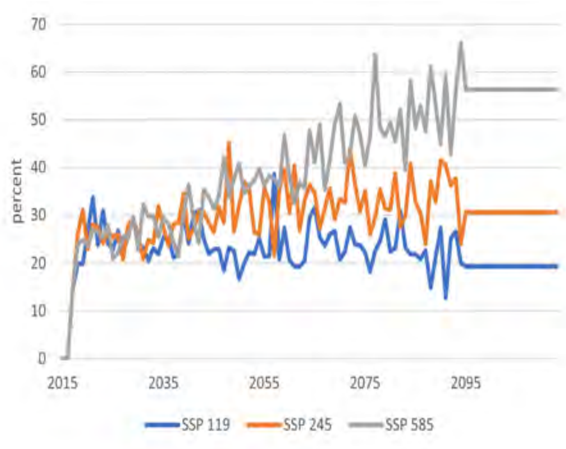
Rice: Crop yield simulations for the Mekong River Delta compute damages by different SSP scenarios. For the remaining regions, crop yield losses depend on the respective region's annual temperature change. In addition to the crop yield model estimates, we consider land loss due to rising sea levels. Therefore the damage function for rice is given by (55).

Figure 5: Land loss due to sea-level rise



Source: National expert, GSO and own computation.

Figure 6: Damage rice crop yield model for Mekong River Delta ($\eta^D_{SSP,1,6,t}$)



Source: Sectoral experts.

$$D_{1,r,t} = \begin{cases} \eta^D_{1,r,t} = \eta^D_{SSP,1,r,t} + 1(\eta^{SL}_t \in b) \sum_{b=2}^{20} ll_{b,1,r}, & \text{if } r = 6 \\ \eta^D_{1,r,t} = 0.03\, \eta^{tas}_{r,t} + 1(\eta^{SL}_t \in b) \sum_{b=2}^{20} ll_{b,1,r}, & \text{if } r \neq 6. \end{cases} \tag{55}$$

A decline in total factor productivity in the sector by 3 % for a 1°C captures the damage to the rice sector except for the Mekong River Delta. Figure 6 depicts Damages computed by the crop yield model.

Other annual crops: Other annual crops, excluding rice, are mainly soybean and maise. Damages caused by an increase in yearly temperature on maise and soybean are the weighted average of the single impacts with the value added share of soybean and maise as weights. In 2014 the share of soybean on value added of other annual crops was 20 percent and of maise 80 percent. Therefore, (56) reports the impact of an increase in the average yearly temperature on crop yields.

$$D_{2,r,t} = \eta^D_{2,r,t} = \underbrace{0.07}_{=1-(0.031\times0.2+0.08\times0.8)} \eta^{tas}_{r,t} + 1(\eta^{SL}_t \in b) \sum_{b=2}^{20} ll_{b,2,r}. \tag{56}$$

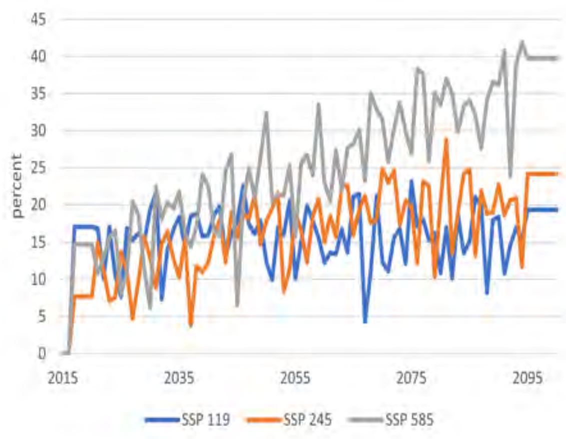
Fruit tree: Zhao et al. (2017) does not explicitly include fruit trees. Therefore, damage to fruit trees results from land loss due to rising sea levels. In addition, the sectoral expert provided damages by different SSP scenarios for the Mekong River Delta. We use the simulated damages for the Mekong River Delta as we did for rice.

$$D_{3,r,t} = \begin{cases} \eta^D_{3,r,t} = \eta^D_{SSP,3,r,t} + 1(\eta^{SL}_t \in b) \sum_{b=2}^{20} ll_{b,3,r}, & \text{if } r = 6 \\ \eta^D_{3,r,t} = 1(\eta^{SL}_t \in b) \sum_{b=2}^{20} ll_{b,3,r}, & \text{if } r \neq 6. \end{cases} \tag{57}$$

Figure 7 depicts damage to fruit trees in the Mekong River Delta.

Dry rubber and other perennial crops: There is no information about the impact of temperature by Zhao et al. (2017) and the applied crop yield model for dry rubber and other perennial crops. Therefore the effect on the respective crops only depends on the land loss caused by sea level rise.

Figure 7: Damage fruit tree crop yield model for Mekong River Delta ($\eta^D_{SSP,3,6,t}$)



Source: Sectoral experts.

$$D_{s,r,t} = \eta^D_{s,r,t} = 1(\eta^{SL}_t \in b) \sum_{b=2}^{20} ll_{b,s,r},\ for\, s \in \{4,\, 6\}. \tag{58}$$

Coffee: Coffee is another important commodity produced in Vietnam. In the Central Highlands, there are different ways to grow coffee. For the analysis, the sectoral experts differentiate between traditional coffee, coffee durian intercropping traditional, coffee-durian intercropping - water-saving irrigation and durian with water-saving irrigation. In the DGE-CRED model, coffee is simulated without representing the subtypes explicitly. Therefore the overall impact of all coffee types is considered. We use a weighted average of the climate change impacts to illustrate the damage caused in different SSP scenarios on coffee production in the Central Highlands. The weights represent the share of the planted area by each subtype. We use the shares provided by the sectoral experts for the year 2020.[21] While traditional coffee is negatively affected by climate change, the other types are positively affected.

$$D_{5,r,t} = \begin{cases} \eta^D_{5,r,t} = \eta^D_{SSP,5,r,t}, & \text{if } r = 4 \\ \eta^D_{5,r,t} = 0, & \text{if } r \neq 4. \end{cases} \tag{59}$$

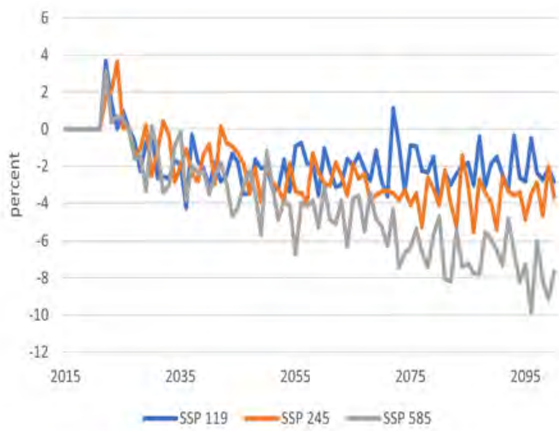
The damages/benefits caused by climate change on coffee production in the Central Highlands are depicted in Figure 8.

Adaptation: There are different ways to adapt to climate change in the agricultural sector. One way to adapt to climate change is to switch production from the more affected sectors to the less affected industries or regions in Vietnam. The DGE-CRED model assumes optimising agents. It implies endogenous adaptation to climate change through disinvestment from highly vulnerable to less vulnerable sectors. Further, it is possible to compensate for the total factor productivity loss with more capital stock investments. So far, most adaptation measures for the agricultural sector consider private action, which is implicitly modelled by optimising agents. According to the national government's land use plan, the land share of traditional coffee should decline from 38 to 26 per cent by 2050. Figure 9 depicts the evolution of land use shares by coffee type. Reducing the share of traditional coffee and replacing it with the other types leads to more benefits for coffee production in the Central Highlands.

Therefore, the overall damage considering adaptation measures in the coffee sector by switching from traditional coffee to other coffee types is a straightforward adaptation measure. Figure 9 depicts the damage/benefit caused by climate change on coffee.

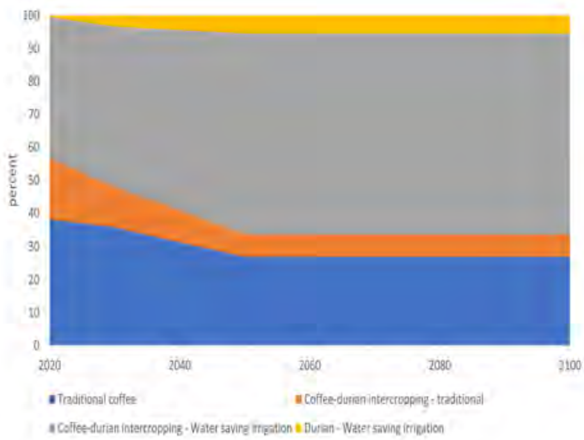
[21] For the year 2020 38.1% of the planted area grew traditional coffee, about 18.5% coffee-durian intercropping-traditional, 43% coffee-durian intercropping- water saving and 0.4% durian - water-saving irrigation.

Figure 8: Damage fruit tree crop yield model for Mekong River Delta ($\eta^{D}_{SSP,5,4,t}$)



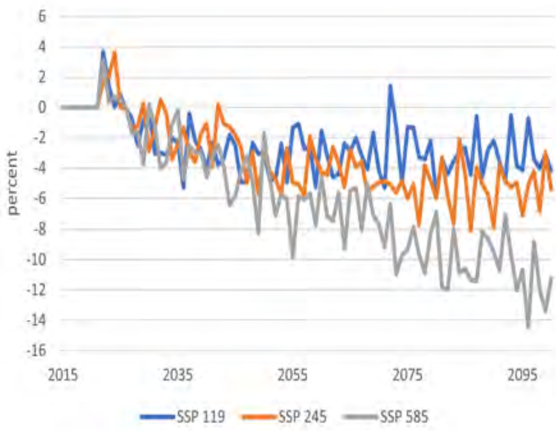
Source: Sectoral experts.

Figure 9: Share of land by coffee types



Source: Sectoral experts.

Figure 10: Damages to coffee with adaptation ($\eta^D_{SSP,5,4,t}$)



Source: Sectoral experts.

3.3.4 Forestry

The forestry sector in Vietnam is responsible for 1.6 % of the gross national value added. More than 30 % of the output in the sector is exported to other countries. National experts differentiate between seven types of forests in Vietnam: evergreen broad-leaved forest, coniferous forest, deciduous broad-leaved forest, bamboo forest, flooded forest, plantation forest. Figure 11 shows the distribution forests across Vietnam.

Forest fires are the main hazard to the forestry sector in Vietnam. In order to quantify the impact of climate change on the forestry sector, we need to know the potential change in the frequency of forest fires. Therefore, we use the so-called Keetch-Byran Drought-Index (KBDI).[22] This index is used to predict the risk of forest fires and depends on the daily maximum temperature T_t^{MAX}, annual average rainfall R_0 and a rainfall factor RF_t, depending on the daily rainfall R_t. We use the modified index for tropical ecosystems Taufik et al. (2015)

$$KBDI_t = KBDI_{t-1} + \frac{(203 - KBDI_{t-1}) \cdot (0.492 \cdot e^{(0.095 \cdot T_t^{MAX} + 1.6096)} - 4.268) \cdot 10^{-3}}{1 + 10.88 \cdot e^{-0.001736 \cdot R_0}} - RF_t.$$

In the following, we describe how we compute the fire frequency using the daily KBDI index for each province.

1. We compute the KBDI for each region using daily surface temperature and daily precipitation. In order to obtain daily predicted precipitation, we use monthly predicted precipitation and use the relative historic daily distribution of precipitation with respect to the average monthly precipitation. In the next step, we compute the daily KBDI for each province. We combine the historically computed KBDI for each province with a dataset of the burned area by the province in Vietnam published by `globalforestwatch.org`. The dataset is used to evaluate the predictive power of the KBDI to forecast fires in Vietnam. The regression results show that the KBDI has predictive power. However, the R^2 is 0.32 and, therefore, indicates only moderate explanatory power. For our simulation study, we will use instead of a regression analysis conditional probabilities. This allows us to capture the potential impact of climate change on the likelihood of forest fires and, at the same time to get reliable estimates of the number of forest fires to be expected. In the literature, a KBDI index value above 150 indicates good conditions for a forest fire.

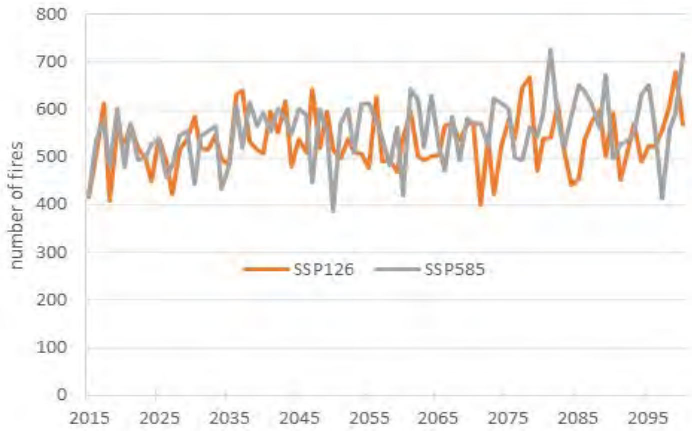
2. The dataset from `globalforestwatch.org` reports burned areas on a weekly frequency. We sum up the KBDI for different weeks and compute the probabilities that a fire occurred conditional on a

[22] Keetch & Byram (1968) introduces the index to measure the severity of droughts.

Figure 11: Map of forests in Vietnam

Source: National experts report for the forestry sector.

Figure 12: Number of forest fires in Vietnam per year



Source: own computation.

weekly KBDI exceeding $1050 = 150 * 7$ and being below the threshold. We estimate the conditional probability of fire given that the KBDI exceeds the threshold to be $P(fire = 1|KBDI > 150*7) = 0.42$. For the case that the index is below the threshold we estimate $P(fire = 1|KBDI < 150*7) = 0.15$.

3. Now, we use the computed daily KBDI to simulate fires in each week from 2014 onwards until 2100 based on the climate variables for the SSP scenario. A fire occurs with a probability of 42 % if the cumulative KBDI for this week exceeded the threshold and only with a probability of 15 % if the KBDI is below 150. We sum up overall provinces belonging to one region for each year to get the predicted number of fires for each year.

4. To evaluate the damage forest fires can create on the forestry sector, it is necessary to know the expected loss in forest area due to fire. Therefore, we compute the median area burned for a fire in each region from 2000 to 2014. In case a fire occurs, this area will be burned. Nevertheless, it is necessary to relate this area to the total area of land used for forestry in the region. Therefore, we use the land use data for each province to get the land used for forestry.

5. The damage due to forest fire in the forestry sector for each region is computed by multiplying the number of forest fires $\eta_{r,t}^{fire}$ in the region for the respective year with the fraction of land burned $ll_{r,t}^{fire}$ from the historical database.

$$D_{9,r,t} = \eta_{9,r,t}^{D} = \eta_{r,t}^{fire}\, ll_{r,t}^{fire}. \tag{60}$$

Figure 12 depicts the evolution of forest fires based on the simulation of the KBDI index and the conditional probabilities estimated.

Adaptation: Forest fires mainly happen in plantation forests. According to the Vietnam Administration of Forestry, about 20,000 ha of natural forest burned between 2002 to 2011. In the same period, about 32,500 ha of plantation forest burned. National experts identified five different adaptation measures to reduce the risk of a forest fire. Table 8 reports all adaptation measures. All adaptation measures are evaluated according to their technical feasibility, local approval and based on the previous two categories. We see that from all adaptation measures, the first one received a very high rating. This adaptation measure considers converting single species forests to mixed plantations consisting of native species and with lower fire risk and higher survival rates.

The share of forestry land loss due to forest fires with and without adaptation for each region is tabulated in Table 9. After the implementation of the first adaptation measure, the share of land loss due to forest fire will be lower. The reduction is based on the historically observed ratio between forest fires occurring in natural forests and plantation forests ($\frac{20{,}000ha}{32{,}500} = 61\,\%$).

Table 8: Adaptation measures

Adaption measure	Technically feasible	Local approval	Ratings
convert single species forests and plantation forests into mixed plantations	High	High	Very high
specialize in trade of natural forests with higher water retention and moisture retention	High	Low	Medium
integrated fire prevention techniques	High	Medium	High
research on technologies for useful use of forest burning	Medium	Low	Low
strengthen communication and education in forest fire prevention and fighting	Medium	Medium	Medium

Source: Doanh et al. (2020).

Table 9: Forestry land loss due to forest fires

Region	without adaptation	with adaptation
Red River Delta	0.104%	0.064%
Northen Midland and Mountain area	0.003%	0.002%
Northen Central and Central Coastal Area	0.003%	0.002%
Central Highlands	0.016%	0.010%
South East	0.020%	0.012%
Mekong River Delta	0.191%	0.117%

Source: Doanh et al. (2020), GSO, globalforestwatch.org and own computation.

The necessary adaptation expenditures are reported in Table 10. They are computed considering the costs of changing one hectare of pure eucalyptus forests to mixed forests with eucalyptus and pine. We assume that the cumulative adaptation measures expressed relative to GDP in 2014 will reduce the burned area for each fire according to the factor computed with the historical data for the period 2001 to 2010. Therefore, the damage induced by a fire is

$$D_{9,r,t} = \eta^D_{9,r,t} = \begin{cases} ll^{fire,na}_{r,t} \, fire_{r,t} & \text{,if } \sum_{h=0}^{t} G^A_{h,r} < G^A_{Total,r}, \\ ll^{fire,a}_{r,t} \, fire_{r,t} & \text{,if } \sum_{h=0}^{t} G^A_{h,r} \geq G^A_{Total,r}. \end{cases} \tag{61}$$

After the adaptation measures have been implemented, the burned area per fire in the region reduces to the respective value reported in Table 9. However, the adaptation measures only reduce the burned area after completion of the adaptation measure. The implementation of the adaptation measure, according to the experts, takes ten years.

Table 10: Adaptation expenditures in the forestry sector $\frac{G^A_{r,t}}{P_0 Y_0}$

Period	Red River Delta	Northern Midland and Mountain area	Northen Central and Central Coastal Area	Central Highlands	Southeast	Mekong River Delta
1	0.0140	1.5396	0.8889	0.0000	0.0000	0.0000
2	0.0070	0.7674	0.4431	0.0000	0.0000	0.0000
3	0.0043	0.4706	0.2717	0.0000	0.0000	0.0000
4	0.0018	0.1998	0.1154	0.0000	0.0000	0.0000
5	0.0012	0.1374	0.0793	0.0000	0.0000	0.0000
6	0.0111	1.2178	0.7031	0.0000	0.0000	0.0000
7	0.0001	0.0115	0.0066	0.0000	0.0000	0.0000
8	0.0001	0.0115	0.0066	0.0000	0.0000	0.0000
9	0.0001	0.0115	0.0066	0.0000	0.0000	0.0000
10	0.0117	1.2893	0.7444	0.0000	0.0000	0.0000
Total	0.0515	5.6560	3.2669	0.0000	0.0000	0.0000

Source: Doanh et al. (2020).
Note: Adaptation expenditures are expressed in relation to 2014 GDP of Vietnam.

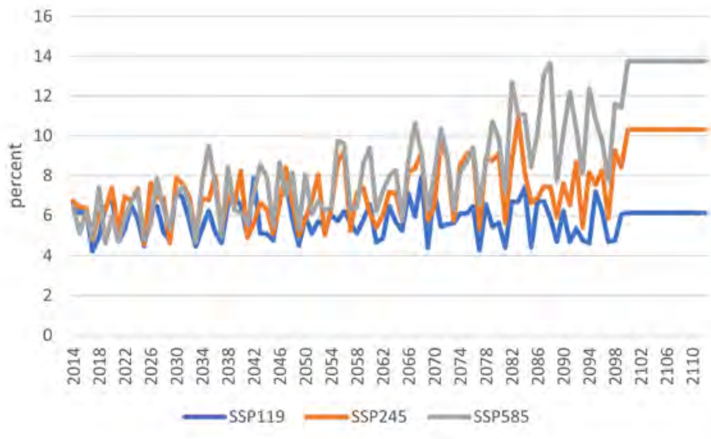
3.3.5 Housing

The home-ownership rate in Vietnam is above 90 %.[23] This implies that the residential buildings are not rented out to firms to provide rental services. They are mainly durable goods consumed by households. Therefore, climate hazards to the housing stock in Vietnam will not affect the capital stock of a specific sector primarily.

Storms: Sectoral experts identify two main hazards to the housing stock in Vietnam. Storms destroy regularly houses in Vietnam. According to scetoral experts the damage caused by storms in Vietnam amounts to 4.65 trillion VND per year in the past. A suitable measure to reflect the impact of storms on the people in Vietnam is the share of affected people. The Potsdam Institute for Climate Change (PIK) provides simulation results for the share of persons affected by storms in Vietnam for the SSP 119, 245 and 585 scenario. Sectoral experts estimate that the expected damage of a storm in Vietnam is 4.65 trillion VND per year. Given that about 5.4 percent of the population was affected by storms according to the PIK measure in the past the damage per affected person is 890 Thousand VND per affected person. The damage induced by storms in the housing stock is the share of affected persons times the damage caused per affected person by a storm relative to GDP in 2014 $D^{H,storms} = \frac{0.89 Million\, VND}{GDP_{2014}}$. We simulate the share of affected persons by storms for the different SSP scenarios.

[23] Source: `https://www.globalpropertyguide.com/Asia/Vietnam/Price-History`

Figure 13: Share of affected persons by storms ($\eta_t^{Storms,SSP}$)



Source: Potsdam Institute for Climate Change simulation results.

We use these values and define them as the potential damage storms can produce in the region. However, the total damage to the national housing stock is given by

$$D_t^H = \eta_t^{D^H} = \eta_t^{Storms,SSP} D^{H,storms}. \tag{62}$$

Sea level: In addition to storms, the sea-level rise will increase the number of floods. This will also destroy parts of the houses in the affected areas. Here, the sectoral experts again assume that roughly 10 % of the houses affected by the floods will be destroyed. We obtained the potential damage for a house given a sea-level rise of 50 cm. This level of sea-level rise will only occur at the earliest stage in 70 years in the SSP 585 scenario. It is very unlikely that intermediate levels of sea-level rise have no impact on the housing stock. Therefore, we use the share of land loss in the construction sector for different bins of sea-level rise. We need to assume a uniform distribution of houses across the total land used for construction. We use the share of construction land loss for a specific range of sea-level rise to estimate the costs. Table 11 reports the damages to the housing stock for each region for different sea levels.

Therefore, damages to the housing stock in Vietnam evolve by

$$D_t^H = \eta_t^{Storms,SSP} D^{H,storms} + \sum_{b=2}^{20} (1(SL_{b-1} < SL_t \leq SL_b) D_b^{H,SL}). \tag{63}$$

Adaptation: For sea-level rise and storms, there are two different adaptation measures. It is possible to build houses with reinforced walls and bricks to reduce the vulnerability of houses to storms. An appropriate measure to reduce the impact of an increase in sea-level rise is to raise a house on stilts. We use the estimated costs and benefits reported in Table 22 and 23 in the Appendix. We will reduce the damages caused by sea-level rise or storms by the respective benefits associated with the necessary cumulative costs for the adaptation measures. Therefore (64), the following equation describes the damages on the housing stock, including adaptation measures.

$$D_t^H = \eta_t^{Storms,SSP} D^{H,storms} - (\sum_{\tau}^{t} G_\tau^{A,H,Storms} < \sum_{\iota}^{p} G_\iota^{A,H,Storms}) min(B_1^{A,H,Storms} \dots, B_t^{A,H,Storms}) \dots$$
$$+ \sum_{b=2}^{20} (1(SL_{b-1} < SL_t \leq SL_b) D_b^{H,SL} * (\sum_{\tau}^{t} G_\tau^{A,H,SL} < G_b^{A,H,SL})). \tag{64}$$

Table 11: House destruction by sea-level rise relative to GDP in 2014

SLR in cm (SL_b)	Red River Delta	Northern midland and mountain area	Northern Central area and Central coastal area	Central Highlands	South East	Mekong River Delta	Vietnam $D_b^{H,SL}$
0	0.000	0.000	0.001	0.000	0.000	0.042	0.043
5	0.001	0.000	0.001	0.000	0.000	0.077	0.079
10	0.002	0.000	0.003	0.000	0.000	0.181	0.186
15	0.004	0.000	0.004	0.000	0.001	0.282	0.290
20	0.005	0.000	0.005	0.000	0.001	0.480	0.492
25	0.007	0.000	0.006	0.000	0.002	0.502	0.517
30	0.008	0.000	0.007	0.000	0.003	0.537	0.555
35	0.009	0.000	0.008	0.000	0.004	0.575	0.596
40	0.011	0.000	0.009	0.000	0.005	0.633	0.659
45	0.013	0.000	0.011	0.000	0.006	0.705	0.734
50	0.014	0.000	0.012	0.000	0.007	0.812	0.846
55	0.016	0.000	0.014	0.000	0.008	0.927	0.965
60	0.019	0.000	0.015	0.000	0.009	1.035	1.078
65	0.021	0.000	0.017	0.000	0.010	1.127	1.175
70	0.024	0.000	0.018	0.000	0.011	1.249	1.302
75	0.026	0.000	0.020	0.000	0.012	1.359	1.418
80	0.029	0.000	0.022	0.000	0.014	1.469	1.534
85	0.032	0.000	0.023	0.000	0.015	1.558	1.629
90	0.035	0.000	0.025	0.000	0.016	1.637	1.714
95	0.039	0.000	0.036	0.000	0.024	1.696	1.795

Source: Nam, Long, Sam, Hai & Hai (2021) and own computation.

3.3.6 Transport

Sea-level rise, temperature, landslides: In Vietnam, the transportation sector is responsible for about 11 % of gross value added. Transportation via roads makes up over 90 %. However, climate change poses a threat to the conditions of the road stock in Vietnam. All damages on the road stock are incorporated through damages to the capital stock of the transport land sub-sector ($D^K_{10,r,t}$). Three different climate hazards have been identified by Nam et al. (2020). First, sea-level rise can flood some of the roads. Second, consecutive days with temperatures above 30°C and more can destroy the asphalt due to melting. Third, landslides as a response to higher precipitation can destroy part of the roads as well. A further distinction by the national experts have been provided regarding the types of road (national roads, highways and provincial roads) and their vulnerability (very low, low, medium, high, very high). However, for the simulation, we aggregate damages and costs across road types and their vulnerability classification. We assign subjective probabilities for different vulnerability classes to compute expected damages on the road stock. In order to link the climate variables from the meteorological model to the specific hazards identified, we first select suitable proxies for each climate hazard. For high temperatures, we use the maximum number of heatwaves in a year as a proxy. The damages caused on the road stock induced by higher temperatures materialize if heatwaves exceed the 90 % quantile of the simulated distribution for the SSP 126 scenario. For the damages induced by landslides, we use the maximum consecutive wet days as a proxy. The sectoral experts provide with the potential damages which alternate across years. This is straightforward for sea-level rise. Here we use the change in sea level to determine the damage on the road stock due to flooding. We computed expected damages across all road types per km^2. In the next step, we multiply the area in km^2 of road loss due to a specific sea-level rise to approximate costs and benefits. Table 24 reports the expected damages for different sea levels.

For the climate hazard high temperatures, we use the maximum number of heatwaves in a year as a proxy. The damages caused on the road stock induced by higher temperatures materialize if heatwaves exceed the 90 % quantile of the simulated distribution for the SSP 126 scenario. Table 13 reports the expected damages caused by heatwaves on the road stock relative to 2014 GDP. According to the table, annual heatwaves above the 90 percent quantile will lead to damages of about 0.025 % relative to GDP in the Red River Delta.

For the damages induced by landslides, we use the maximum consecutive wet days as a proxy. The sectoral experts provide us with damages which alternate across years. In order to link the damages to an observable climate variable, we first identify the $\frac{1}{30}, \ldots, \frac{15}{30}, \ldots \frac{30}{30}$ percentiles of the distribution for maximum consecutive wet days for each region. 30 different distinct values for damages induced by landslides in Vietnam are ordered. If the simulated climate maximum consecutive wet days falls into the respective percentile, we choose the corresponding value for the damages reported by the sectoral experts. The respective damages for each percentile are reported in Table 14. Landslides mainly occur in mountainous areas and not at the coastline. Further, the implied damage to the road stock is negligible in relation to GDP.

Damages caused by climate change without adaptation to the road stock of a region is represented by (65)

$$\begin{aligned} D^K_{15,r,t} = &\sum_{b=2}^{20}(1(SL_{b-1} \geq SL_t < SL_b)D^{SL,Road}_{b,r})\dots \\ &+ 1(heatwave_{r,t} > heatwave^{90,SSP126}_r)D^{heatwave,Road}_r\dots \\ &+ \sum_{p=2}^{30}(1(maxwetdays^{p-1,SSP126}_r < maxwetdays_{r,t} \leq maxwetdays^{p,SSP126}_r)D^{landslide,Road,p}_r). \end{aligned} \tag{65}$$

Adaptation: We simulate adaptation measures for each climate hazard. Each adaptation measure is funded by government expenditures $G^A_{15,r,t} = G^{A,SL}_{15,r,t} + G^{A,heatwave}_{15,r,t} + G^{A,landlside}_{15,r,t}$ in each region. The adaptation measures will reduce the damage induced by the specific hazards. We distinguish between the three different categories. First, an adaptation measure to tackle the sea-level rise is to elevate the affected roadbed by the respective increase. We assume that the roadbed elevation can be done successively before the sea-level rises. The implementation of the adaptation measure will reduce the potential damage for the respective sea level to zero. Second, the adaptation measure to tackle heatwaves and extraordinarily high temperatures is to replace conventional asphalt concrete with poly mere asphalt concrete. At the moment the project starts, the damage by high temperatures to the road network goes to zero. According to the sectoral experts, the implementation of the adaptation measure only takes two years. This short period justifies this simplification. Third, effective measures against road erosion can mitigate the impact of landslides on the road stock in Vietnam. The implementation takes only a year, and the costs are relative to GDP in 2014 negligible. Equation (66) reports damages with adaptation measures.

$$\begin{aligned} D^K_{15,r,t} = &\sum_{b=2}^{20}(1(SL_{b-1} \geq SL_t < SL_b)D^{SL,road}_{b,r})1(\sum_{\tau}^{t} G^{A,SL}_{15,r,\tau} < G^{A,SL,b}_{15,r}))\dots \\ &+ 1(heatwave_{r,t} > heatwave^{90,SSP126}_r)D^{heatwave,road}_r 1(\sum_{\tau}^{t} G^{A,heatwave}_{15,r,\tau} < G^{A,heatwave,total}_{15,r,\tau})\dots \\ &+ \sum_{p=2}^{20} 1(maxwetdays^{p-1,SSP126}_r < maxwetdays_{r,t} \leq maxwetdays^{p,SSP126}_r)D^{landslide,road,p}_r)\dots \\ &+ 1(\sum_{\tau}^{t} G^{A,landslide}_{15,r,\tau} < G^{A,landslide,total}_{15,r,\tau}) \end{aligned} \tag{66}$$

Table 12: Damages caused by sea-level rise to the road stock

SLR	Red River Delta	Northern midland and mountain area	Northern coastal and coastal area	Central Highlands	South East	Mekong River Delta
			Damages/Benefits			
0	0.001	0.000	0.002	0.000	0.001	0.002
5	0.001	0.000	0.004	0.000	0.003	0.004
10	0.001	0.000	0.008	0.000	0.006	0.009
15	0.002	0.000	0.010	0.000	0.010	0.014
20	0.002	0.000	0.013	0.000	0.017	0.023
25	0.003	0.000	0.016	0.000	0.018	0.025
30	0.004	0.000	0.020	0.000	0.020	0.029
35	0.004	0.000	0.023	0.000	0.021	0.031
40	0.005	0.000	0.027	0.000	0.023	0.035
45	0.006	0.000	0.032	0.000	0.024	0.040

Table 12: Damages caused by sea-level rise to the road stock

SLR	Red River Delta	Northern midland and mountain area	Northern coastal and coastal area	Central Highlands	South East	Mekong River Delta
50	0.007	0.000	0.036	0.000	0.027	0.044
55	0.008	0.000	0.039	0.000	0.029	0.048
60	0.009	0.000	0.044	0.000	0.032	0.053
65	0.011	0.000	0.048	0.000	0.034	0.058
70	0.012	0.000	0.052	0.000	0.037	0.063
75	0.014	0.000	0.056	0.000	0.040	0.068
80	0.015	0.000	0.062	0.000	0.043	0.074
85	0.017	0.000	0.067	0.000	0.045	0.080
90	0.019	0.000	0.071	0.000	0.048	0.086
95	0.021	0.000	0.083	0.000	0.052	0.095
			Costs			
0	0.001	0.000	0.004	0.000	0.002	0.003
5	0.001	0.000	0.003	0.000	0.003	0.004
10	0.001	0.000	0.008	0.000	0.006	0.008
15	0.001	0.000	0.004	0.000	0.008	0.011
20	0.001	0.000	0.005	0.000	0.014	0.019
25	0.001	0.000	0.006	0.000	0.002	0.003
30	0.001	0.000	0.008	0.000	0.003	0.004
35	0.001	0.000	0.006	0.000	0.002	0.003
40	0.001	0.000	0.007	0.000	0.004	0.005
45	0.002	0.000	0.010	0.000	0.003	0.005
50	0.002	0.000	0.007	0.000	0.005	0.007
55	0.002	0.000	0.007	0.000	0.004	0.006
60	0.003	0.000	0.008	0.000	0.005	0.007
65	0.003	0.000	0.009	0.000	0.004	0.006
70	0.003	0.000	0.007	0.000	0.006	0.008
75	0.003	0.000	0.008	0.000	0.005	0.007
80	0.004	0.000	0.012	0.000	0.006	0.008
85	0.004	0.000	0.009	0.000	0.005	0.007
90	0.004	0.000	0.009	0.000	0.006	0.008
95	0.004	0.000	0.021	0.000	0.008	0.011

Source: Nam et al. (2020) and own computation.

Table 13: Damages caused by heatwaves on road stock

Period after start	Red River Delta	Northern midland and mountain area	Northern coastal and coastal area	Central Highlands	South East	Mekong River Delta
			Damage by extraordinary heatwaves			
heatwave	0.025	0.071	0.060	0.038	0.024	0.033
			Adaptation benefits			
1	0.000	0.000	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.000	0.000
3	0.006	0.018	0.015	0.010	0.006	0.008
4	0.006	0.018	0.015	0.010	0.006	0.008
5	0.006	0.018	0.015	0.010	0.006	0.008
6	0.025	0.071	0.060	0.038	0.024	0.033
7	0.006	0.018	0.015	0.010	0.006	0.008
8	0.006	0.018	0.015	0.010	0.006	0.008
9	0.006	0.018	0.015	0.010	0.006	0.008
10	0.025	0.071	0.060	0.038	0.024	0.033
11	0.006	0.018	0.015	0.010	0.006	0.008
12	0.006	0.018	0.015	0.010	0.006	0.008
13	0.006	0.018	0.015	0.010	0.006	0.008
14	-0.008	-0.022	-0.019	-0.012	-0.008	-0.010
15	0.006	0.018	0.015	0.010	0.006	0.008
16	0.006	0.018	0.015	0.010	0.006	0.008
17	0.006	0.018	0.015	0.010	0.006	0.008
18	0.025	0.071	0.060	0.038	0.024	0.033
19	0.006	0.018	0.015	0.010	0.006	0.008
20	0.006	0.018	0.015	0.010	0.006	0.008
21	0.006	0.018	0.015	0.010	0.006	0.008
22	0.025	0.071	0.060	0.038	0.024	0.033
23	0.006	0.018	0.015	0.010	0.006	0.008

Table 13: Damages caused by heatwaves on road stock (cont.)

Period after start	Red River Delta	Northern midland and mountain area	Northern coastal and coastal area	Central Highlands	South East	Mekong River Delta
24	0.006	0.018	0.015	0.010	0.006	0.008
25	0.006	0.018	0.015	0.010	0.006	0.008
26	-0.008	-0.022	-0.019	-0.012	-0.008	-0.010
27	0.006	0.018	0.015	0.010	0.006	0.008
28	0.006	0.018	0.015	0.010	0.006	0.008
29	0.006	0.018	0.015	0.010	0.006	0.008
30	0.025	0.071	0.060	0.038	0.024	0.033
Period			Costs			
1	0.012	0.033	0.029	0.018	0.012	0.016
2	0.018	0.050	0.043	0.026	0.017	0.024

Source: Nam et al. (2020) and own computation.

Table 14: Damages caused by landslides and cost of adaptation measures

Percentile after start	Red River Delta	Northern midland and mountain area	Northern coastal and coastal area	Central Highlands	South East	Mekong River Delta
3%	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
7%	0.00000	0.00021	0.00000	0.00001	0.00000	0.00000
10%	0.00000	0.00007	0.00000	0.00000	0.00000	0.00000
13%	0.00000	0.00033	0.00000	0.00002	0.00000	0.00000
17%	0.00000	0.00008	0.00000	0.00000	0.00000	0.00000
20%	0.00000	0.00009	0.00000	0.00000	0.00000	0.00000
23%	0.00000	0.00035	0.00000	0.00002	0.00000	0.00000
27%	0.00000	0.00011	0.00000	0.00001	0.00000	0.00000
30%	0.00000	0.00011	0.00000	0.00001	0.00000	0.00000
33%	0.00000	0.00038	0.00000	0.00002	0.00000	0.00000
37%	0.00000	0.00013	0.00000	0.00001	0.00000	0.00000
40%	0.00000	0.00014	0.00000	0.00001	0.00000	0.00000
43%	0.00000	0.00040	0.00000	0.00002	0.00000	0.00000
47%	0.00000	0.00016	0.00000	0.00001	0.00000	0.00000
50%	0.00000	0.00017	0.00000	0.00001	0.00000	0.00000
53%	0.00000	0.00043	0.00000	0.00002	0.00000	0.00000
57%	0.00000	0.00019	0.00000	0.00001	0.00000	0.00000
60%	0.00000	0.00020	0.00000	0.00001	0.00000	0.00000
63%	0.00000	0.00046	0.00000	0.00002	0.00000	0.00000
67%	0.00000	0.00022	0.00000	0.00001	0.00000	0.00000
70%	0.00000	0.00023	0.00000	0.00001	0.00000	0.00000
73%	0.00000	0.00049	0.00000	0.00003	0.00000	0.00000
77%	0.00000	0.00025	0.00000	0.00001	0.00000	0.00000
80%	0.00000	0.00026	0.00000	0.00001	0.00000	0.00000
83%	0.00000	0.00053	0.00000	0.00003	0.00000	0.00000
87%	0.00000	0.00029	0.00000	0.00002	0.00000	0.00000
90%	0.00000	0.00031	0.00000	0.00002	0.00000	0.00000
93%	0.00000	0.00058	0.00000	0.00003	0.00000	0.00000
97%	0.00000	0.00074	0.00000	0.00004	0.00000	0.00000
100%	0.00000	0.00076	0.00000	0.00004	0.00000	0.00000
Year			Cost			
1	0	0.00076	0	0.000048	0	0

Source: Nam et al. (2020) and own computation.

3.3.7 Dyke

In Vietnam the dyke system is about 54,457 km long (p.1 Nam, Long, Sam & Tuan 2021). The geographical characteristics of the country make it necessary to have a functioning and extensive dyke system. Dykes secure against floods and storm surges. River dyke systems make up over 10% of the total dyke system in Vietnam. The most commonly used method to protect used land from floods and storm surges are embankments. Embankments are earth walls and represent about 80% of the dyke system in Vietnam. Sea dykes represent roughly about 1,000 km of the current dyke system in Vietnam.

Nam, Long, Sam & Tuan (2021) report that raising dyke's with a medium to high vulnerability to flooding for a sea-level rise of 50 cm can eliminate potential land losses. In order to assess the potential damage caused by sea-level rise on the region's land loss, computations based on geographical information systems are used.

As discussed in the previous subsections the sea level rise will affect different sectors in Vietnam. Therefore, measures to improve the dyke system in Vietnam represents an adaptation measure affecting agriculture, transport and the capital stock of the industry.

Adaptation: Nam, Long, Sam & Tuan (2021) reports the necessary investments to upgrade the existing dyke structure in Vietnam to make it more resilient to an increase in the sea level by 50 cm. The experts considered all dykes in Vietnam with a medium, high and very high vulnerability to an increase in the sea level rise by 50 cm. They computed the additional investment requirements for each region reported in Table 27

Adaptation measures in the dyke sector directly reduce the damages in the agriculture, housing, transport and industry sector. Therefore, damages in the sectors are affected in the following way

$$D_{1,r,t} = \begin{cases} \eta^D_{1,r,t} = \eta^D_{SSP,1,r,t} + 1(\sum_\kappa^t G^A_{13,r,\kappa} < \sum_\kappa^t G^{Dyke}_{13,r,\kappa})^{\eta^{SL}_t < 50} 1(\eta^{SL}_t \in b) \sum_{b=2}^{20} ll_{b,1,r}, & \text{if } r = 6 \\ \eta^D_{1,r,t} = 0.03\, \eta^{tas}_{r,t} + 1(\sum_\kappa^t G^A_{13,r,\kappa} < \sum_\kappa^t G^{Dyke}_{13,r,\kappa})^{\eta^{SL}_t < 50} 1(\eta^{SL}_t \in b) \sum_{b=2}^{20} ll_{b,1,r}, & \text{if } r \neq 6. \end{cases} \tag{67}$$

$$D_{2,r,t} = \eta^D_{2,r,t} = \underbrace{0.07}_{=1-(0.031\times 0.2+0.08\times 0.8)} \eta^{tas}_{r,t} + 1(\sum_\kappa^t G^A_{13,r,\kappa} < \sum_\kappa^t G^{Dyke}_{13,r,\kappa})^{\eta^{SL}_t < 50} 1(\eta^{SL}_t \in b) \sum_{b=2}^{20} ll_{b,2,r}. \tag{68}$$

$$D_{3,r,t} = \begin{cases} \eta^D_{3,r,t} = \eta^D_{SSP,3,r,t} + 1(\sum_\kappa^t G^A_{13,r,\kappa} < \sum_\kappa^t G^{Dyke}_{13,r,\kappa})^{\eta^{SL}_t < 50} 1(\eta^{SL}_t \in b) \sum_{b=2}^{20} ll_{b,3,r}, & \text{if } r = 6 \\ \eta^D_{3,r,t} = +1(\sum_\kappa^t G^A_{13,r,\kappa} < \sum_\kappa^t G^{Dyke}_{13,r,\kappa})^{\eta^{SL}_t < 50} 1(\eta^{SL}_t \in b) \sum_{b=2}^{20} ll_{b,3,r}, & \text{if } r \neq 6. \end{cases} \tag{69}$$

$$D^K_{10,r,t} = 2634 \frac{10^9 VND}{km^2} \sum_{b=2}^{20} ll_b^{SL,Manu} 1(SL_b < SL_t \leq SL_{b+1}) 1(\sum_\kappa^t G^A_{13,r,\kappa} < \sum_\kappa^t G^{Dyke}_{13,r,\kappa})^{\eta^{SL}_t < 50} \tag{70}$$

$$\begin{aligned} D^K_{15,r,t} = {} & 1(\sum_\kappa^t G^A_{13,r,\kappa} < \sum_\kappa^t G^{Dyke}_{13,r,\kappa})^{\eta^{SL}_t < 50} \sum_{b=2}^{20} (1(SL_{b-1} \geq SL_t < SL_b) D^{SL,road}_{b,r}) 1(\sum_\tau^t G^{A,SL}_{15,r,\tau} < G^{A,SL,b}_{15,r})) \dots \\ & + 1(heatwave_{r,t} > heatwave_r^{90,SSP126}) D_r^{heatwave,road} 1(\sum_\tau^t G^{A,heatwave}_{15,r,\tau} < G^{A,heatwave,total}_{15,r,\tau}) \dots \\ & + \sum_{p=2}^{20} 1(maxwetdays_r^{p-1,SSP126} < maxwetdays_{r,t} \leq maxwetdays_r^{p,SSP126}) D_r^{landslide,road,p}) \dots \\ & + 1(\sum_\tau^t G^{A,landslide}_{15,r,\tau} < G^{A,landslide,total}_{15,r,\tau}) \end{aligned} \tag{71}$$

$$\begin{aligned} D^H_t = {} & \eta_t^{Storms,SSP}\, D^{H,storms} - (\sum_\tau^t G_\tau^{A,H,Storms} < \sum_\iota^p G_\iota^{A,H,Storms}) min(B_1^{A,H,Storms} \dots, B_t^{A,H,Storms}) \dots \\ & + 1(\sum_\kappa^t G^A_{13,r,\kappa} < \sum_\kappa^t G^{Dyke}_{13,r,\kappa})^{\eta^{SL}_t < 50} \sum_{b=2}^{20} (1(SL_{b-1} < SL_t \leq SL_b) D_b^{H,SL} * (\sum_\tau^t G_\tau^{A,H,SL} < G_b^{A,H,SL})). \end{aligned} \tag{72}$$

The adaptation measure in the dyke sector is only able to reduce damages induced by flooding due to sea level rise for sea levels below 50 cm. Therefore, if the sea level exceeds 50 cm, damages will materialise.

3.3.8 Drainage

The model incorporates potential damages by rain-induced floods to urban areas in Vietnam. Thanh et al. (2020) analyse the results of three case studies conducted in the Mekong River Delta to evaluate the effect of sustainable urban drainage systems. Case studies are located in Long Xuyen (An Giang province), Rach Gia (Kien Gang province) and Ca Mau (Ca Mau province). All three cities are located in the Mekong River Delta region. Rainy days in urban areas can cause floods in the city due to sealed floors. Sustainable urban drainage systems reduce the water flow in the city. Adaptation measures include a self-permeable rainwater harvesting garden, permeable pavement structure and an underground water tank. The three measures in combination can reduce the water flow in urban areas by up to 25% (Thanh et al. 2020, p.101). Table 15 summarises the main findings of the pilot projects. Sustainable urban drainage systems are able to reduce the impacted area by floods. Floods occur as a consequence of excessive rainfall. The project team assumes that at 70% of rainy days in the area, there is a flood. The pilot projects show that the impacted area on average is reduced to 13% of the original area. Households impacted by floods are determined by the number of households per square kilometre times the flooded area. Therefore, the drainage system reduces the number of impacted households per flood. Further, the average duration of the flood is reduced. Floods reduce the available days to work and eventually to earn income. Infrastructure and houses exposed to floods need to be repaired more frequently. A reduction of the flooded area leads to a reduction in the number of houses and buildings with higher operation and maintenance costs due to floods. The maintenance cost of houses relative to their original value is 2% without flooding and 5% with flooding. Infrastructure exposed to flooding has maintenance costs of 6% relative to its original value and without flooding 3.66%. Therefore sustainable urban drainage systems reduce the maintenance and operation costs of flooded houses and infrastructure but also the number of houses and infrastructure flooded.

Table 15: Sustainable urban drainage system pilot project evaluation

Regions	Long Xuyen	Rach Gia	Ca Mau
households	8734	7203	5657
area (km^2)	6.28	3.31	2.08
cultivated area (km^2)	3.31	1.75	2.08
impacted area (km^2) without project	0.01375	0.00953	0.020670
Flooded area (km^2) without project	0.00250	0.00238	0.00104
Flooded area (km^2) with project	0.0005	0.00048	0.00021
impacted Households without project	6.59668	9.78785	2.81762
impacted Households with project	1.31934	1.95922	0.56298
number of rainy days	132	159	185
number of floods	92	111	130
Damages			
housing without project (billion VND/year)	0.119	0.177	0.051
housing with project (billion VND/year)	0.024	0.035	0.010
infrastructure without project (billion VND/year)	0.048	0.045	0.020
infrastructure with project (billion VND/year)	0.010	0.009	0.004
damage lost time of households without project (person days per year)	0.59553	0.88363	0.25437
damage lost time of households with project (person days per year)	0.02382	0.03537	0.01016
Costs			
capital expenditure (billion VND per year)	2.679	2.597	1.325
operation and maintenance (billion VND per year)	0.041	0.019	0.039

Source: Thanh et al. (2020) and own computation.

Table 25 reports the assumptions to compute the benefits and costs of adaptation measures in the drainage sector on a regional level. Table 16 reports results of the upscaling for the six statistical regions in Vietnam. In order to compute the impacted area, the urban area of the region is multiplied by 80%. Further, we compute the regional flooded area share for each region by multiplying 13.45% times the relative precipitation per square kilometre of the region to the precipitation in the Mekong River Delta.

The implementation of the project in the urban regions reduces the flooded area by 80 %. The number of impacted households in each region is determined by the number of households per km^2 multiplied by the flooded area in the respective region. The number of impacted households times the difference of maintaining and operation costs of a newly constructed house exposed and not exposed to a flood. Damages on infrastructure area equal to the flooded area times the urban investment rate per square kilometre times the difference in the depreciation rate for a flooded and a non-flooded urban area. The number of rainy days per year in the Mekong River Delta is the average across the three pilot projects. For the other regions, we compute the average precipitation per square kilometre from 1985 to 2014 and relate it to the average precipitation for the same time period in the Mekong River Delta. We assume that the rainy days per year across the regions are directly proportional to the precipitation per square kilometre. The loss in time is equivalent to the number of impacted households times the average household size times the duration of the flood with and without the adaptation measure. The implementation costs of the project depend on the impacted area in each region, times the average construction cost per square kilometre from the three pilot projects. Operation and maintenance costs are 1.52% of the initial capital expenditure costs.

Table 16: Sustainable urban drainage system upscaling results

Regions	Mekong River Delta	Red River Delta	North Central and Central coastal areas	Northern midlands and mountain areas	Central Highlands	South East
population	4328087	7856566	5719511	2280853	1676242	11198476
households urban	684996	1687257.5	870399	227763	167556	2209879
urban area (km^2)	256	352	217	72	79	175
average housing area (m^2/house)	82	97	101	116	99	67
impacted area (km^2)	205	282	173	57	63	140
flooded area (km^2) without project	28	38	23	8	9	19
flooded area (km^2) with project	6	8	5	2	2	4
impacted households without project	73726	181600	93681	24514	18034	237849
impacted households with project	14745	36320	18736	4903	3607	47570
precipitation (mm)	2181	1336	1467	1322	1961	2150
number of rainy days	159	97	107	96	143	157
number of floods ($floods_r$)	111	68	75	67	100	110
Damages						
housing without project (billion VND/flood) ($D_r^{\text{H,flood,without SUD}}$ billion VND/flood)	12.00	57.03	27.79	9.33	3.91	32.00
housing with project (billion VND/flood) ($D_r^{\text{H,flood,with SUD}}$ in billion VND/flood)	2.40	11.41	5.56	1.87	0.78	6.40
infrastructure without project (billion VND/flood) ($D_r^{\text{Infra,flood,without SUD}}$ in billion VND/flood)	4.72	10.62	5.93	2.19	1.62	3.26
infrastructure with project (billion VND/flood) ($D_r^{\text{Infra,flood,with SUD}}$ in billion VND/flood)	0.94	2.12	1.19	0.44	0.32	0.65
lost time without project (person days per flood) ($D_r^{\text{N,flood,without SUD}}$ in person days/flood)	59.96	241.09	112.76	33.03	16.28	195.20
lost time with project (person days per flood) ($D_r^{\text{N,flood,with SUD}}$ in person days/flood)	2.40	9.64	4.51	1.32	0.65	7.81
Project Costs						
capital expenditure (billion VND) ($CAPEX_r^{Drainage}$)	36362.63	50099.76	30836.45	10187.33	11259.36	24861.59
operation and maintenance cost (billion VND per year) ($OM_r^{Drainage}$)	551.86	760.35	467.99	154.61	170.88	377.32

Damages: In order to include the impact of floods and adaptation measures in the drainage sector into the model we need to translate the damages from floods caused by rainy days into model variables. First we will define the number of floods $floods_{r,t}$ in each region as follows

$$floods_{r,t} = \frac{per_{r,t}}{\frac{1}{30}\sum_{t=1985}^{2014} per_{r,t}} floods_r. \tag{73}$$

The number of floods in a given simulation year is directly proportional to the precipitation in the year relative to the arithmetic mean from 1985 to 2014. Years with extraordinary high precipitation will experience more floods in the respective year and vice versa. We now compute damages to the housing stock by

$$D_t^{H,flood} = \sum_r floods_{r,t} \frac{D_r^{\text{H,flood,without SUD}}}{GDP_{2014}}. \tag{74}$$

For simplicity, we assume that damages to the urban infrastructure are captured mainly by damages to roads. Therefore, damages induced by floods affect the road stock directly in the respective region

$$D^{K,flood}_{15,r,t} = floods_{r,t}\,\frac{D^{\text{Infrastructure, without SUD}}_{r}}{GDP_{2014}}. \tag{75}$$

The loss in time in a region due to the exposure of floods is captured by reductions in the labour productivity of the region in the non-primary sub-sectors. Therefore, damages to labour productivity caused by floods is

$$D^{N,flood}_{s,r,t} = floods_{r,t}\,\frac{D^{\text{N, without SUD}}_{r}}{PoP_{r,2020}\,365.25},\ for\,s \in [5,\ldots,12]. \tag{76}$$

Here we standardise the days per flood lost by the number of days per year and the population in the respective region for the year 2020.

Adaptation: the implementation of sustainable urban drainage systems requires region-specific capital expenditure costs $CAPEX^{Drainage}_{r}$ and annual operation and maintenance costs $OM^{Drainage}_{r}$. After the implementation, the functioning of the drainage system depends on the consecutive expenditure of the operation and maintenance costs. The government adaptation expenditure for the drainage sector is part of the expenditures for the water supply sub-sector $G^{A}_{5,r,t}$. The evolution of government expenditures for adaptation measures is as follows

$$G^{A}_{10,r,t} = \begin{cases} CAPEX^{Drainage}_{r} & \text{if } t = 1 \\ OM^{Drainage}_{r} & \text{if } t > 1 \end{cases} \tag{77}$$

The damages created by floods on the housing and infrastructure stock depends on the cumulative expenditures for adaptation measures, as well as the losses in labour productivity. Damages are now experessed by

$$l^{sum,exp} = \sum_{\iota}^{t} G^{A}_{10,r,\iota} - (CAPEX^{Drainage}_{r} + (t-1)OM^{Drainage}_{r}), \tag{78}$$

$$D^{H,flood}_{t} = \sum_{r} floods_{r,t}\,\frac{1(l^{sum,exp} \geq 0)\,D^{\text{H,flood,with SUD}}_{r} + 1(l^{sum,exp} < 0)\,D^{\text{H,flood,without SUD}}_{r}}{GDP_{2014}}, \tag{79}$$

$$D^{K,flood}_{15,r,t} = floods_{r,t}\,\frac{1(l^{sum,exp} \geq 0)D^{\text{Infra, without SUD}}_{r} + 1(l^{sum,exp} < 0)D^{\text{Infra, with SUD}}_{r}}{GDP_{2014}}, \tag{80}$$

$$D^{N,flood}_{s,r,t} = floods_{r,t}\,\frac{1(l^{sum,exp} \geq 0)D^{\text{N, without SUD}}_{r} + 1(l^{sum,exp} < 0)D^{\text{N, with SUD}}_{r}}{PoP_{r,2020}\,365.25},\ for\,s \in [10,\ldots,17]. \tag{81}$$

If cumulative adaptation expenditures in the drainage sector exceed the capital expenditures plus the operation and maintenance expenditures, the damages by flooding are reduced. The successful implementation of sustainable urban drainage systems allows reducing the flooded area by 80%. Further, the flood duration is reduced by 80% as well.

3.3.9 Scenarios

In addition to the Baseline scenario, we will simulate in total 25 different scenarios. Table 17 reports all 25 scenarios. The Baseline scenario only considers the evolution of the Vietnamese economy without climate change. The climate change scenarios SSP 119, 245 and 585 represent the evolution of climate variables and their impact on the different sectors, as discussed in the previous sections. We implement adaptation scenarios, where we only consider adaptation measures for one respective field and all adaptation measures at the same time. We do this also for each SSP scenario. This allows us to see the adaptation measures with the highest impact on GDP in Vietnam.

Table 17: Overview of Scenarios

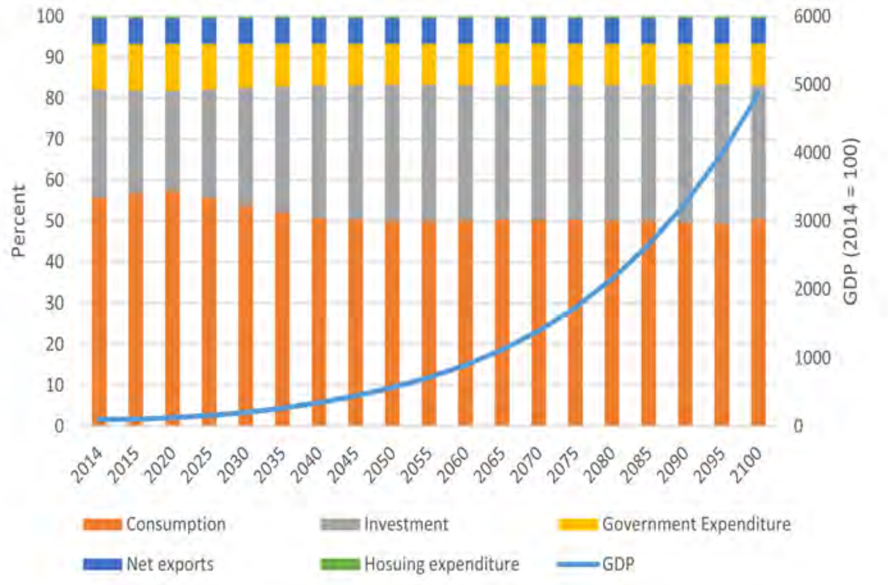
Name	Description
Baseline	Development of the Vietnamese economy without impacts of climate change on the economic development. The net export to GDP ratio remains constant. Sectoral growth rates are depicted in Figure 14. Further, the housing area per person remains the same.
SSP 119	Climate variables evolve according to the shared socio-economic pathway 119. Damages are incorporated for each sub-sector.
SSP 245	Climate variables evolve according to the shared socio-economic pathway 245. Damages are incorporated for each sub-sector.
SSP 585	Climate variables evolve according to the shared socio-economic pathway 585. Damages are incorporated for each sub-sector.
SSP 119, 245, 585 Adaptation Housing	Climate variables evolve according to the shared socio-economic pathway 119, 245,585. Damages are incorporated for each sub-sector and only adaptation measures for the housing sector are implemented
SSP 119, 245, 585 Adaptation Transport	Climate variables evolve according to the shared socio-economic pathway 119, 245, 585. Damages are incorporated for each sub-sector and only adaptation measures for the transport sector are implemented
SSP 119, 245, 585 Adaptation Drainage	Climate variables evolve according to the shared socio-economic pathway 119, 245, 585. Damages are incorporated for each sub-sector and only adaptation measures for the urban drainage system are implemented
SSP 119, 245, 585 Adaptation Dyke	Climate variables evolve according to the shared socio-economic pathway 119, 245, 585. Damages are incorporated for each sub-sector and only adaptation measures for the dyke system are implemented
SSP 119, 245, 585 Adaptation Coffee	Climate variables evolve according to the shared socio-economic pathway 119, 245, 585. Damages are incorporated for each sub-sector and only adaptation measures for the coffee sector are implemented
SSP 119, 245, 585 Adaptation All	Climate variables evolve according to the shared socio-economic pathway 119, 245, 585. Damages are incorporated for each sub-sector and all adaptation measures are implemented

3.4 Results

3.4.1 Baseline

The model simulates an exponential growth path through the development of sectoral productivity. This reflects the fact that developing countries increase their productivity by deploying knowledge and production technologies from already developed economies. It implicitly also assumes higher human capital formation. However, this increase in exogenous productivity of the primary production factors capital and labour triggers more investment into the capital stock, which also contributes to the growth of the economy. A higher GDP, in the long run, leads to higher consumption expenditures and government expenditures. Figure 14 shows an increase in all components of GDP. However, investments in the capital stock grow faster than the other components. The growth rate of GDP and net exports coincides by assumption.

Figure 14: Evolution of key economic indicators



Source: Own computation.

The impact evaluation of different adaptation measures and climate change variables is done with respect to the baseline evolution. This allows evaluating the impact controlling for a change in the composition of sectors. We can see in Figure 15 a faster expansion of the tertiary sector. Especially the services sector will increase. Therefore, Vietnam will move from an economy with a focus on the primary sector to a service-based economy similar to currently developed economies. As a consequence, the share of employment (see Figure 19) in the service industry increases.

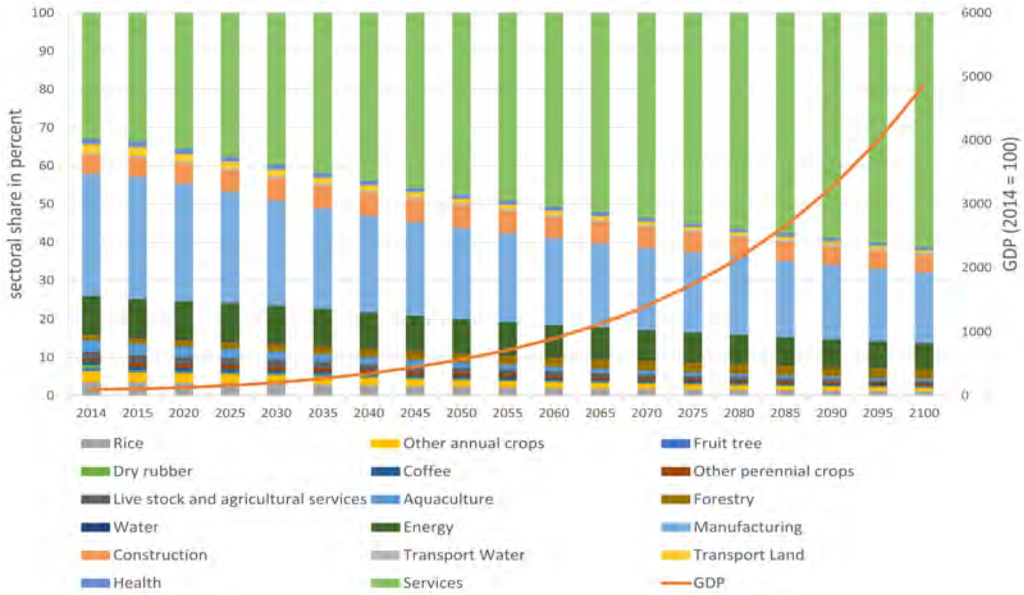
In the following, we present the results for different scenarios. All figures represent deviations from the baseline results.

3.4.2 Damages in Vietnam

The previous sections describe the implementation of different impact channels in the simulation. Figure 16 summarizes the previous section in a graph. The figure shows assumed damages by type relative to GDP in the Baseline scenario. Therefore, it shows how much damages caused by labour productivity, a reduction in total factor productivity, capital destruction or housing stock costs in relation to GDP.

If climate evolves according to the SSP 119 scenario, the direct damage to Vietnam will be stable over the 21st century. From 2020 to 2054, the damage is about 3 to 4 percent of the annual GDP. Here over 50 percent of the observed damage comes from labour productivity, followed by damages caused by a reduction in total factor productivity.

Figure 15: Evolution of sub-sectoral value-added



Source: own computation.

In the SSP 245 scenario, the damages increase over time. However, the main reason for the increase is still an increase in labour productivity. From 2020 to 2054, the damages caused by climate change are similar to the SSP 119 scenario. However, they increase to 5 and 6 percent between 2055 to 2079. At the end of the century, damages reduce GDP on average by 7 percent. The main driver for the increase in damages is labour productivity.

The SSP 585 scenario damages in the first interval are similar to the SSP 119 and SSP 245 scenario, reflecting similar climate variables changes over the period 2020 to 2054. From 2055 to 2100, damages are between 8 and 9 percent. Labour productivity alone contributes more than 6 percent to the damages. Damages excluding labour productivity mainly increase over time due to housing and capital destruction caused by sea level rise.

Adaptation measures do not focus on labour productivity to reduce direct damages. Therefore, the potential of the included adaptation measures to minimise damages by climate change is low in Vietnam. A tremendous potential has adaptation measures to reduce the impact of sea level rise on housing and capital.

3.4.3 Agriculture

The agriculture sector in the model consists of different crops and products represented by various subsectors. Each subsector has another exposure to climate change, as discussed before. The following paragraphs will shorty summarise for each subsector the main simulation results.

Rice Figure 20 shows the damages for rice in different scenarios by regions relative to GDP. Damages caused by climate change to the rice sector mainly appear in the Mekong River Delta. For other areas, the damages are not from a crop yield simulation model but based on the results of a meta-study. In the SSP 119 scenario, the heterogeneous effect of climate change on the rice sector also leads to different responses in value-added relative to the Baseline scenario. Value added in the rice sector in the Mekong River Delta declines by more than 1 percent relative to GDP in the period from 2020 to 2054. The value added impact declines over time relative to GDP because of a lower contribution of rice to total GDP in Vietnam. The rice production in other regions increases due to lower direct impacts of climate change compared to the Mekong River Delta. In the SSP 245 scenario, similar damages relative to GDP are observed, leading to similar simulation results for value-added. The results are qualitatively identical to the SSP 119 scenario. In the SSP 585 scenario, climate change impacts are again mainly dominated by the effects in the Mekong River Delta. However, in contrast to the other scenarios, damages to the Red River Delta increase sufficiently to reduce the value added to the Red River Delta's rice sector. Adaptation measures in the dyke sector can reduce the impact of climate change on rice production. However, the potential damage reduction reflects the availability of more land through avoided land losses caused by sea level rise. The implementation of all adaptation measures at the same time yields no additional benefit for direct damages. None of the considered adaptation measures can avoid the loss in value added in the rice sector in Vietnam. The main threat to the rice sector is not the loss of land or weather extremes. Labour productivity decline due to heat stress is the main threat to the country.

Other annual crops Figure 21 shows the damages for other annual crops by regions relative to GDP. Damages caused by climate change to other annual crops are distributed across the areas in Vietnam according to the initial contribution of the region to value added in the sector. In the SSP 119 scenario, the homogenous effect of climate change on the industry also leads to identical responses in value-added relative to the Baseline scenario. Value added contributed by other annual crops relative to the GDP in Vietnam declines by 0.25 percent from 2020 to 2054. As for the rice sector, the value-added impact declines over time relative to GDP. In the SSP 245 scenario, damages relative to GDP are slightly higher compared to the SSP 119 scenario. Further, a lower contribution to value-added does not compensate for the increasing impact of climate change as in the SSP 119 scenario. Therefore, the effect even increases. Damages in the SSP 585 scenario relative to GDP peak between 2055-2079 decline afterwards. The contribution to the GDP effect can not be compensated by increasing damages due to climate change, especially labour productivity. Adaptation measures in the dyke sector can only reduce direct damages and value-added reductions marginally.

Fruit Tree Figure 22 shows the damages for fruit trees. Damages caused by climate change to fruit trees mainly concentrate in the Mekong River Delta. Therefore the regional distribution of damages and the effect on value-added is similar to the effects on the rice sector. However, climate change's impact is less severe than the impact on rice. Only adaptation measures upgrading the dyke sector can reduce the impact of climate change on fruit trees. The reduction in damages is negligible.

Dry rubber In contrast to fruit trees and rice, damage to dry rubber in the Mekong River Delta does not reflect crop yield simulations. Figure 23 shows that damages to dry rubber are evenly proportional to each region's initial contribution to the value-added generated by dry rubber in Vietnam. Therefore, the impact on value added is also homogenous across the areas. Again only adaptation measures in the dyke sector can reduce the effects of climate change on the industry. All other adaptation measures cannot reduce the impact of climate change.

Coffee One crucial commodity for export is coffee in Vietnam. Damages to the coffee sector vary tremendously with the respective SSP scenario. In the SSP 119 scenario, the direct damages to coffee by climate change are harmful, indicating more favourable climatic conditions to grow coffee in the region. Figure 24 shows that the impact on coffee is positive at the end of the century for the SSP 119 scenario. The reason is that the crop yield simulation model indicates higher crop yields in the Central Highlands, compensating for lower labour productivity due to higher temperatures. Switching from traditional coffee to other coffee types, as noted by the sectoral experts and according to the current land use plans by the central government in Vietnam, leads to even higher crop yields. In addition, the threat of sea level rise is low in the Central Highlands due to high alleviation levels. The impact on gross value added depends on the implemented adaptation measures. Moving away from traditional coffee can increase the coffee production in the Central Highlands, equivalent to 0.3 per cent compared to the SSP 119 scenario, without the implemented adaptation measure by the end of the century. However, for the SSP 585 scenario, direct damages are favourable and therefore indicate a reduction in value-added compared to the Baseline scenario. Changing from traditional coffee to other types can reduce the impact but not eliminate the effect of lower labour productivity.

Other perennial crops, livestock and aquaculture Figures 25 to 26 show damages and the response of value added for the other perennial crops and livestock products in Vietnam. Damages on other perennial crops are mainly due to heat stress. Therefore, potential mitigation measures that reduce land loss due to sea level rise have a low potential to mitigate the damages in the affected areas. The main effect for livestock emerges from lower labour productivity due to heat stress. The regional impact depends on the local temperature change. No adaptation measures have addressed labour productivity in the sector so far. However, adaptation measures in the other sectors can also spill over to those not directly targeted by the actions.

Figure 27 shows damages on the aquaculture sector. No adaptation measure directly targets this sector. Damages relative to GDP in the sector decline over time because of a lower share of the sector to total GDP. Aquaculture in the Mekong Delta exhibits the greatest reduction in gross value added. It also reflects the greatest direct exposure to climate change.

3.4.4 Forestry

Figure 28 shows the expected damages in the forestry sector. The most serious damage is expected in the Northern and Central coastal areas. Roughly 30 per cent and more direct damages occur in the Northern, Central, and Central coastal areas. Direct damages to the forestry sector in Vietnam are between to 0.10 % to 0.12 % (SPP 119), 0.22 % to 0.23 % (SPP 245), and 0.27 % to 0.28 % (SSP 585), respectively. Here, it is assumed that already burned areas can burn again next year; if we assume that already burned areas are less likely to burn again next year, the expected damage increases even further.

In the adaptation scenarios for the forestry sector, we simulate the switch of forests from single species to multiple species forests. Quantification for the costs is not reported for the Central Highlands, the South East, and the Mekong River Delta. For the other regions, the implementation of the adaptation measure will lead to a reduction of burned area per fire by almost 40 %. It has direct consequences for value added in the sub-sector and region. However, the reduction in value-added across all areas is negligible with adaptation measures in the forestry sector. Simultaneously implementing all adaptation measures has the most significant impact on the forestry sector in Vietnam. Therefore, it is possible that spillover effects can have even more significant benefits for the forestry sector.

3.4.5 Manufacturing

Figure 31 shows the expected damages in the manufacturing sector. There are two impact channels considered. One is labour productivity, and the other impact channel is the loss of capital due to sea level rise. The first impact channel dominates the second, indicating a low reduction potential. Adaptation measures in the dyke sector can reduce the loss in capital but not lower the impact of heat stress on the labour productivity of workers in the manufacturing industry. At the beginning of the 21st century, value-added responses are relatively low. It reflects that sea level rise and temperature increases will materialize only in the second half of the 21st century. In contrast to the previous sectors, value-added reductions in the manufacturing industry have non-negligible impacts. In the SSP 585 scenario, the drop in value added in the manufacturing sector can reduce Vietnam's annual GDP by 1.4 percent alone at the end of the century.

3.4.6 Transport

The effects of sea-level rise, temperature, and landslides on the transport sector to the capital stock are shown in Figure 34. Regions with a coastline are affected by floods, while the Central Highlands and the Northern midland and mountain areas road stock is exposed to landslides. At the same time, heat waves destroy the roadbed in all regions. In addition, labour productivity declines due to heat stress. A lower capital stock and lower labour productivity reduce value added in all areas, but mainly in the South East and the Northern central and central coastal regions.

Adaptation measures in the transport sector can tremendously reduce the impact of climate change on value added in the first half of the 21st century. The second half of the 21st-century adaptation measures in the transport sector do not reduce the value-added effects. The decline in other sectors at the end of the century negates the positive impacts of adaptation measures.

3.4.7 Services and Health

The expected damages and value-added reductions in the services and health sector are shown in Figure 35 and Figure 36. Direct damages to the services sector are the main driver of the reduction in GDP in Vietnam due to climate change at the end of the 21st century. Regional decrease in value-added mainly reflects the initial contributions of each region to value added in the services sector. At the end of the 21st century, value added in the services sector can contribute alone up to 8 percent of the reduction in GDP in Vietnam for the SSP 585 scenario. The spill-over effects from adaptation measures targeting other sectors cannot significantly reduce the loss.

3.4.8 Housing

Climate change impacts on the housing stock in Vietnam can be significant. Figure 16 shows that damages to the housing stock at the end of the century amount to almost 1.00 percent in terms of annual GDP in Vietnam for the SSP 585 scenario. In the SSP 245 scenario the damages are only 0.60 percent of annual GDP at the end of the century. More stable climate conditions as assumed in the SSP 119 scenario even indicate an impact of 0.45 percent of annual GDP until the end of the century.

A destruction of the housing stock in Vietnam will not affect directly the production capacities of the country. It will require additional investments in the housing stock to repair for the damages and to provide enough housing space for the residents. Therefore, adaptation measures reducing direct damages to the housing stock as proposed by the sectoral experts will reduce the need for investments into the housing stock. The reduction in investment demand will directly affect the output and GDP in the respective scenario. However, adaptation measures in the housing sector will directly increase demand for construction services and eventually increase GDP in the construction sector ceteris paribus. The simulation results show that the direct demand for construction services induced by the adaptation measures do not compensate the reduction in housing investment (see Figure 32). Lower investment demand for housing implies lower demand for output from other sectors. It implies that adaptation measures can reduce GDP by reducing the demand to repair the damages induced by climate change. Households respond to lower destruction to their housing stock by reducing investments into the housing stocks. This implies at the same time that they choose more leisure compared to a world without the adaptation measure and use their available income more for consumption. Therefore we can observe that hours worked and the capital stock in the scenarios with adaptation measure in the housing sector is lower (see Figure 37).

3.4.9 Macroeconomic effects

To assess the overall macroeconomic effects of climate change, Figure 17 depicts the effect of climate change on the GDP components: consumption, investment, government expenditure, net exports and housing expenditures. For the SSP 119 scenario the simulation results suggest that the impact is relatively stable over the 21st. In this scenario annual GDP will be four to five percent lower compared to the Baseline scenario. At the beginning of the century net exports increase GDP by more than one percent. However, the positive contribution of net exports declines over time. At the end of the century the positive contribution is only 0.50 percent of annual GDP. The main reason for the positive contribution of net exports is a low price elasticity of export demand. Therefore, an increase in relative prices compensates for the decline in the volume of exports. Over time, export-intensive industries contribute less to GDP, and thus the positive contribution to the economic development declines. The primary aggregates consumption and investment both shrink by about 3 and 1 percent, respectively. Government expenditures decline as well as private expenses into housing. Personal payments into housing mainly drop in adaptation scenarios preventing housing the destruction of houses by publicly financed adaptation measures in the housing sector. It is a reflection of the inelastic demand for housing. Adaptation measures reducing the impact of climate change on the housing stock lessen the necessity to privately invest into the housing stock.

GDP declines by four percent in the first half of the 21st century with climate evolving according to the SSP 245 scenario. During the beginning of the second half, the decline is about 7 percent. At the end of the century, GDP declines by about 10 percent. Net exports increase relative to the Baseline scenario, while all other GDP components decline. Mainly consumption and disinvestment are responsible for the observed decrease. Housing adaptation measures do not reduce the negative impact on GDP but increase the effect. The exact mechanisms apply as in the SSP 119 scenario.

GDP impacts in the SSP 585 scenario are around 4.5 percent at the beginning and about 10 percent at the start of the century's second half. GDP declines by more than 12 percent at the end of the 21st century annual. The main impact on GDP is through consumption, representing the greatest component of GDP followed by investment. The SSP 585 scenario poses a severe threat to Vietnam's economic development.

To prioritize adaptation measures by sectors, we look at the potential of the adaptation measure to reduce the gap in consumption between climate change scenarios and the Baseline scenario. We can establish the following ranking reported in Table 18 for the SSP 119, SSP 245 and SSP 585 scenarios.

Table 18: Adaptation measures prioritization

SSP 119 (-3.57%)		SSP 245 (-5.75%)		SSP 585 (-7.47%)	
adaptation	consumption relative to baseline	adaptation	consumption relative to baseline	adaptation	consumption relative to baseline
Coffee	-3.48	Forestry	-5.82	Coffee	-7.38
Forestry	-3.47	Drainage	-5.79	Forestry	-7.37
Transport	-3.47	Coffee	-5.79	Transport	-7.36
Drainage	-3.46	Housing	-5.72	Drainage	-7.35
Housing	-3.40	Transport	-5.70	Housing	-7.25
Dyke	-3.31	Dyke	-5.59	Dyke	-7.17

Source: Own computation.
Note: Average deviation of consumption relative to the Baseline in terms of GDP defined by $\frac{1}{2100-2020}\sum_{t=2020}^{2100}\frac{C_t^{Scenario}-C_t^{Baseline}}{Y_t^{Baseline}}$.

We see that adaptation measures to make the dyke system more resilient reduce the consumption gap more than other adaptation measures. Further, the potential reduction gap is similar across the SSP 585 scenarios. However, the adaptation measures in no sector so far can tremendously reduce the consumption gap. No adaptation measure can offset any of the aforementioned direct impacts to zero. As stated earlier, the main impact channel is labour productivity. None of the adaptation measures directly addresses the losses in labour productivity due to sea level rise. The structural transformation of the Vietnamese economy from an agricultural and labour-intensive economy to a more service-oriented and capital-intensive economy seems to be the best adaptation strategy to reduce the impact of heat on labour productivity.

4 Conclusion and Discussion

4.1 Summary

The DGE-CRED model allows the user to conduct a cost-benefit analysis in a dynamic general equilibrium framework. It requires the translation of damages for each sector in monetary or physical values into meaningful values from a general equilibrium perspective. First, it is necessary to define a baseline scenario to evaluate the impact of climate change and adaptation measures. The baseline scenario requires the definition of sub-sectoral growth rates for value-added and employment shares. Further, it is necessary to define the evolution of net exports to GDP, the population stock and the house area. For Vietnam, we represent the Baseline scenario according to the results of another CGE model provided by national economists.

Users need to decide through which channel a hazard will impact the economy. So far, we include the potential of climate hazards to cause damages to total factor productivity of the sub-sector, labour productivity or the formation of the capital stock and housing stock.

We show in the application for Vietnam that one can include biophysical damages, such as crop yield loss, and land losses due to sea-level rise into productivity losses for different sectors. Further, we show how to incorporate estimated monetary damages to capital and housing stock. It is possible to implement damages as a fraction of current GDP or initial GDP. The most appropriate approach depends on the specific adaptation measure considered.

Our results are well in line with Espagne et al. (2021). For the SSP 245 scenario the estimated reduction in annual GDP is roughly 5 percent. Compared to the world bank estimate of roughly 10 percent GDP reduction in the 2050s for the RCP 4.5 scenario the estimates of this study are far lower. There are multiple reasons for the different results. It is important to investigate the differences in future research to better understand key assumptions and mechanisms in the different models and to foster understanding of the impact channels.

According to the results adaptation measures for the dyke system should have priority to reduce the consumption gap. However, we see that neither the considered adaptation measures targeting dykes, drainage systems, transport infrastructure, housing, and forestry nor the coffee sector can reduce the consumption gap to a relevant magnitude. It implies that damages induced on agriculture and labour productivity are the primary source of consumption reductions in Vietnam due to climate change. Policymakers in Vietnam should focus on adaptation measures for the agricultural sector and reduce labour intensity. So far, the simulation results only consider endogenous adaptation measures.

4.2 Discussion

Our application allows us to evaluate the impact of adaptation measures on other sectors not explicitly considered in the initial cost-benefit analysis. Further, it is not necessary to make assumptions about prices, interest rates and other variables as usually done by standard partial equilibrium cost-benefit analysis. The current version of the model relies on the premise of rational agents with perfect foresight. Policymakers need to acknowledge the assumption and its implications for interpreting the results.

Currently, our assessment relies on the input from sectoral experts evaluating potential damages to the respective sectors in the economy. However, the sectoral reviews are the first trial to translate biophysical knowledge or data on extreme weather destruction into economic impacts. Therefore, future research projects need to extend and improve the approach. Better integration of the different models used to assess and quantify the economic effects is a good point of departure. In addition, more reliable regional economic and climate data is desirable to better determine the regional financial perspective.

Modelling representative households with a clear preference structure and model consistent expectations implies that the transition path of the model represents the most efficient one. It rules out the impact of uncertainty on the decisions of the agents. Under risk aversion, the investment will be more cautious than in a deterministic world. Further, backwards-looking expectations will also reduce the speed of adjustment. Therefore, we can expect that the adjustment process will take longer.

Researchers and policymakers need to inform the public as good as possible about the current scientific basics of climate change and potential adaptation measures. Further, policy measures need to be implemented in a transparent and commonly understandable way. It is necessary to enable agents in the economy to make rational decisions. The credibility of the stability in implementing policy measures is a further prerequisite to making long-run planning possible.

Future versions of the model can allow for a share of irrational agents forming expectations solely on the past or with a behaviour described by simple heuristics. Nevertheless, it is noteworthy that Cobb-Douglas production and utility functions imply constant expenditure shares. Therefore, the suggested response is already a simple rule which means that agents adjust the quantities purchased of a product such that the percentage of total expenditures is constant.

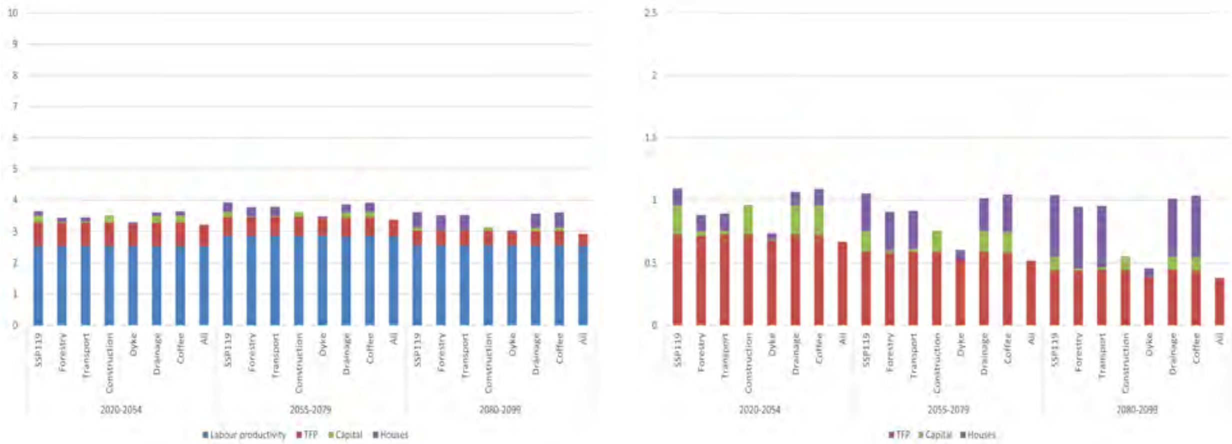
A further modification for future model versions is the explicit incorporation of the implied increase in demand for different sub-sectoral products induced by adaptation expenditures. For instance, one could explicitly account for the higher demand for construction services by employing adaptation measures in the construction sector.

Mitigation policies are not yet explicitly considered. There are potential interdependencies between mitigation and adaptation policies to climate change. Adaptation measures in the forestry sector will help to store GHG emissions and therefore increase the world's carbon budget. Here we did not consider the impact of reducing burned forest area on the storage of CO_2 emissions.

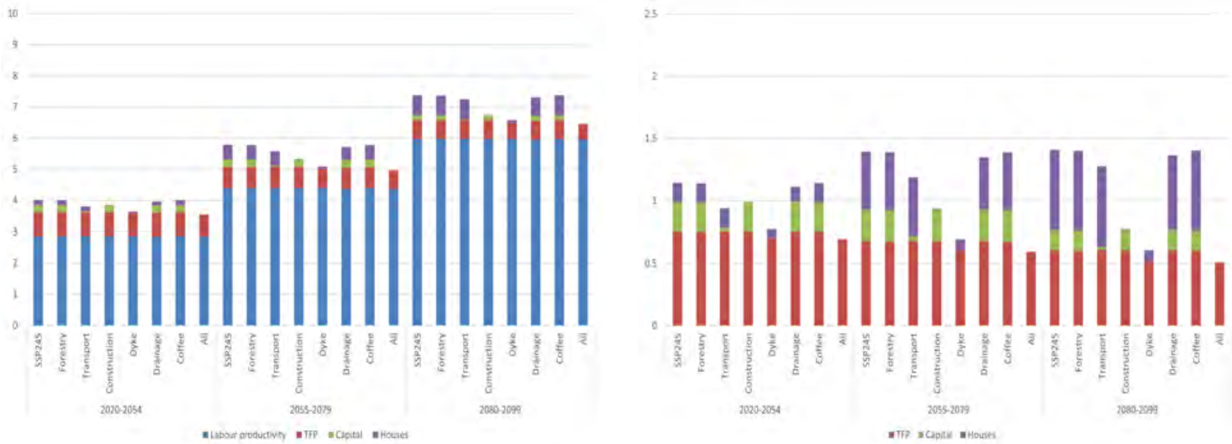
The proposed model is meant to be a point of departure for future research to implement potential damages induced by climate change and adaptation measures to reduce the damages in a transparent and replicable way. The results can be used to conduct a cost-benefit analysis to prioritize adaptation measures between and within sectors.

Figure 16: Damages in Vietnam (percent relative to Baseline GDP)

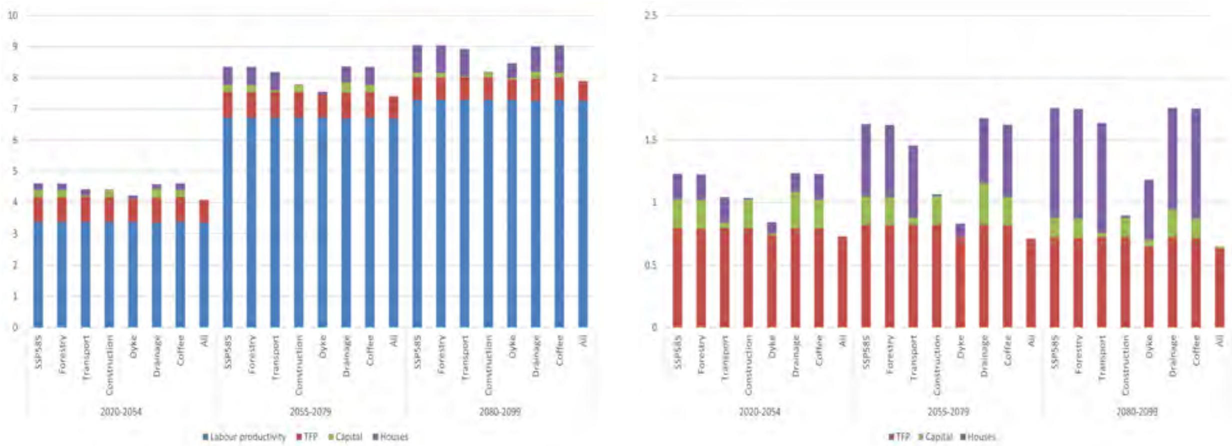
SSP 119



SSP 245



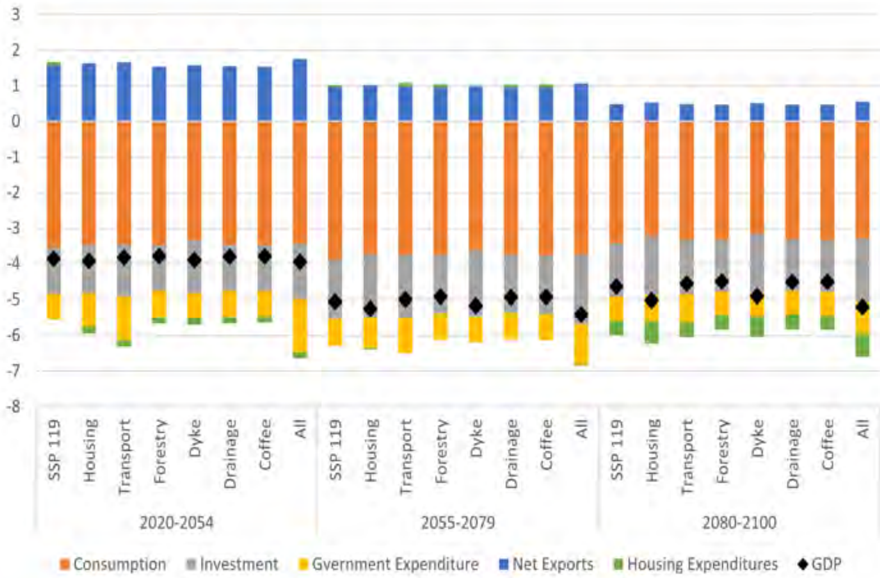
SSP 585



Source: own computation.

Figure 17: GDP components (in percent relative to GDP in the Baseline)

SSP 119



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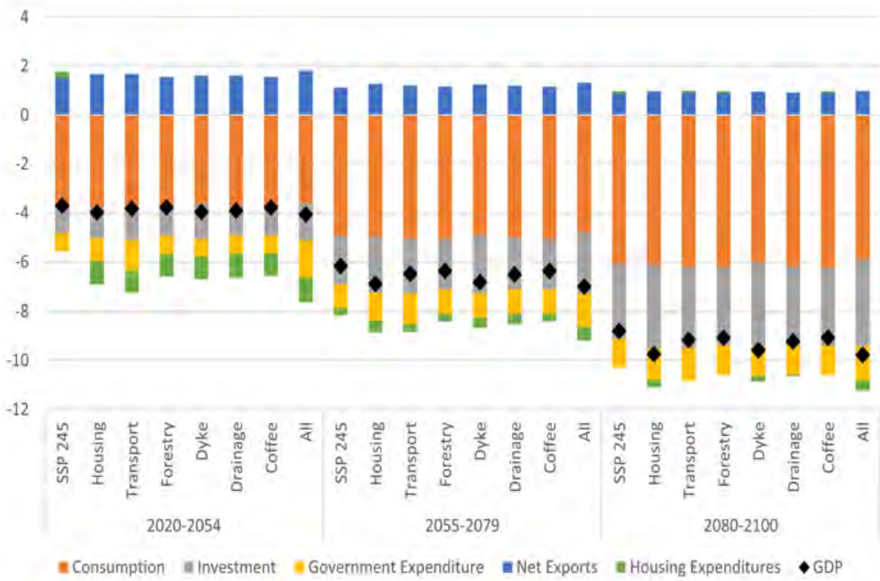

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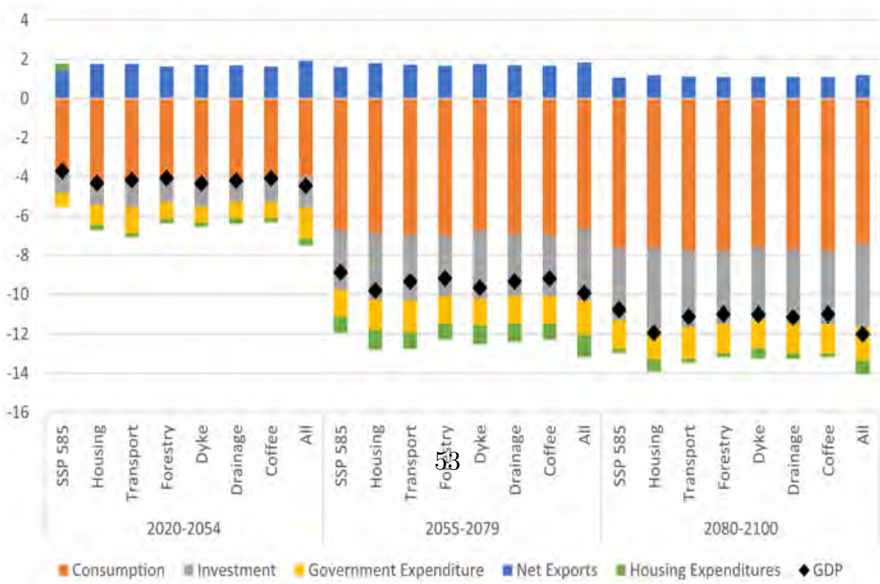

Source: own computation.

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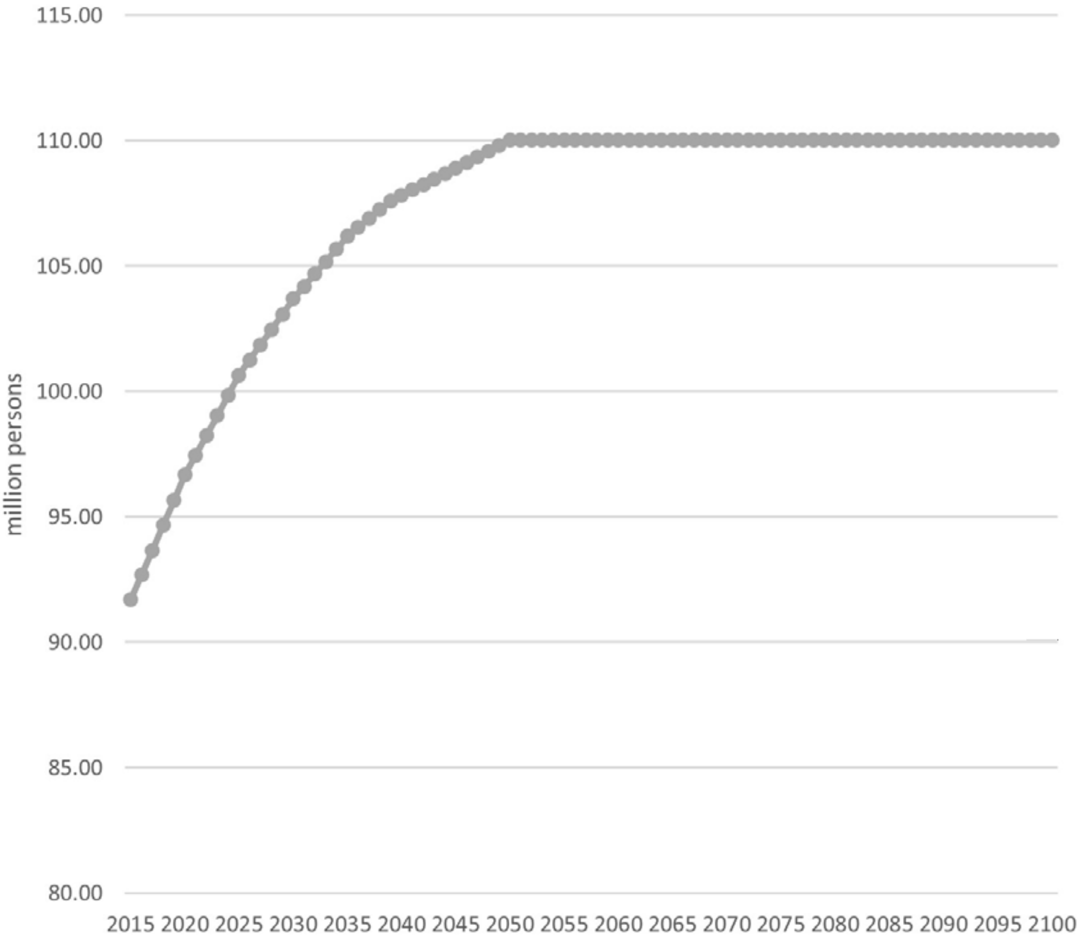
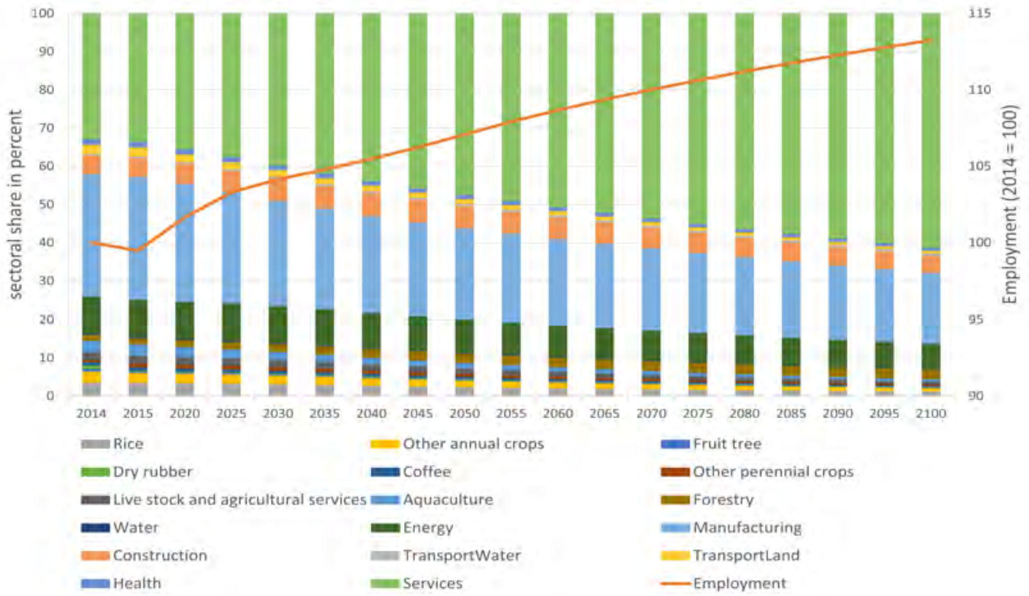
A Figures

Figure 18: Population projection for Vietnam



Source: GSO and United Nations medium fertility variant in Table A.1.

Figure 19: Evolution of sub-sectoral employment

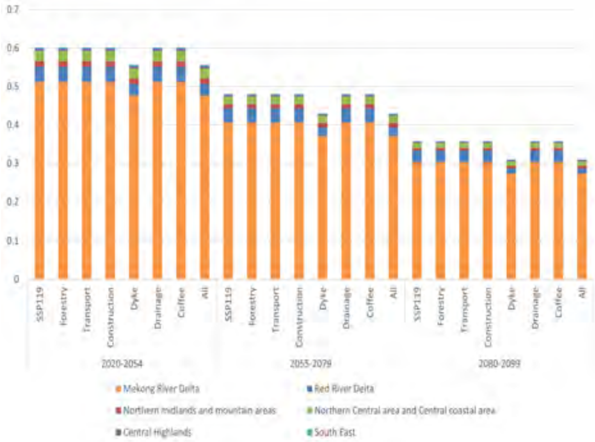


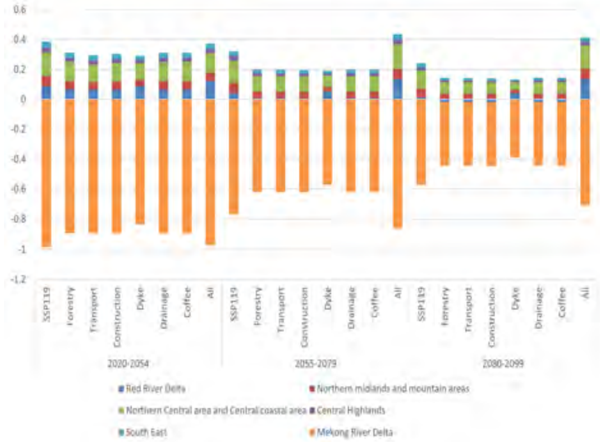
Source: own computation.

Figure 20: Damages and value added rice (in percent relative to GDP in the Baseline)

Damage | Value added

SSP119





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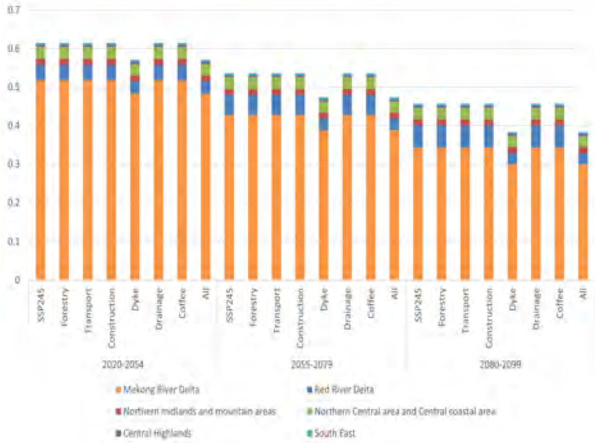

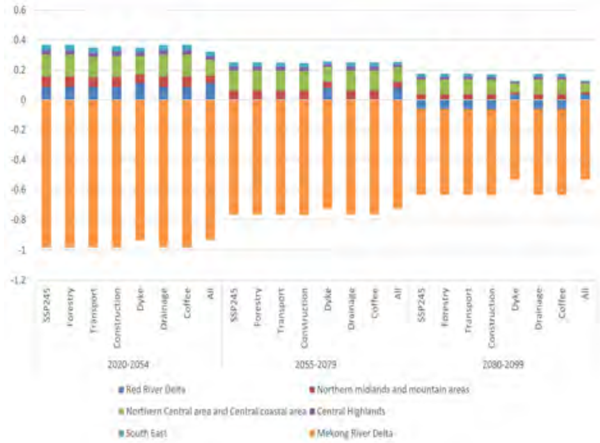

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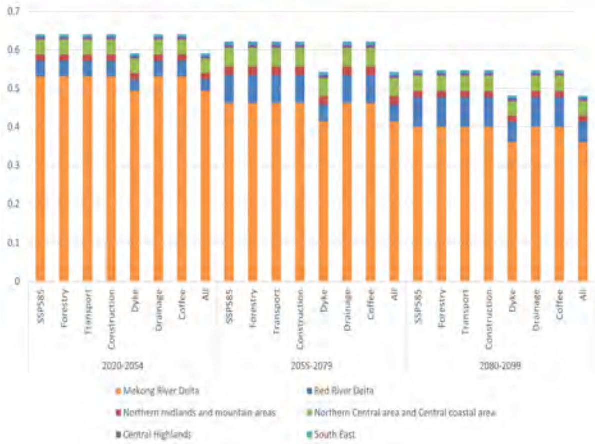
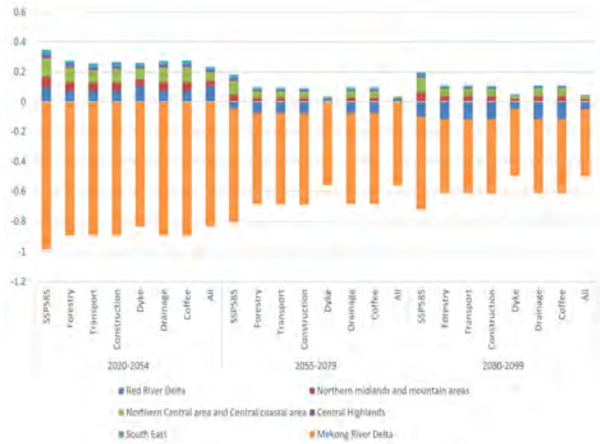


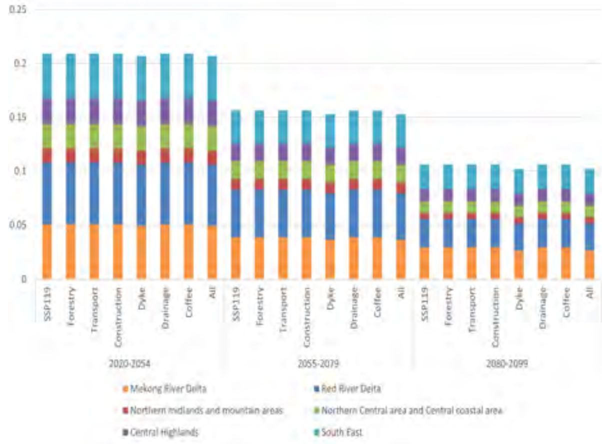


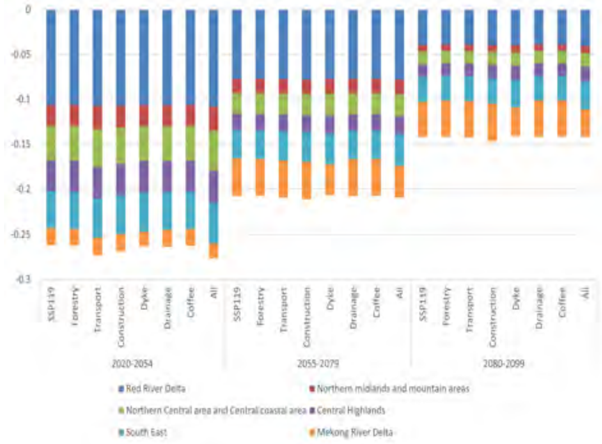
Source: own computation.

Figure 21: Damages and value added other annual crops (in percent relative to GDP in the Baseline)

Damage | Value added

SSP119





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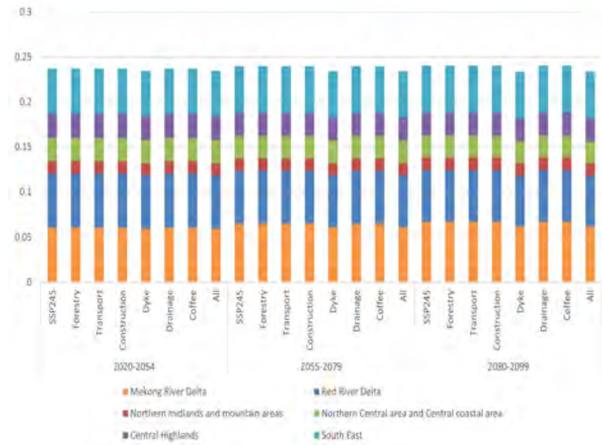

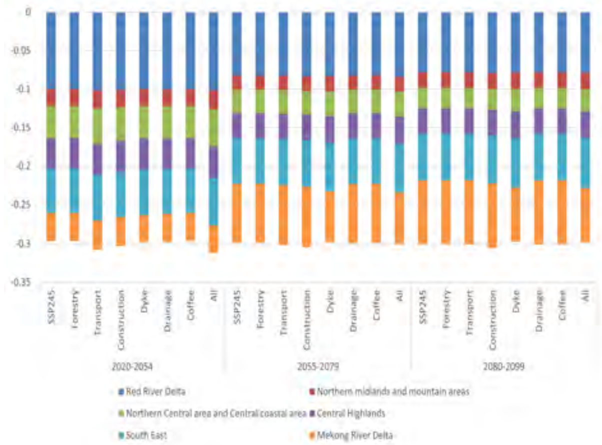

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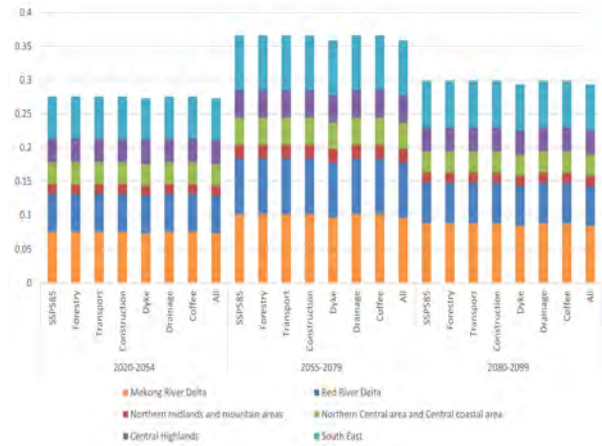
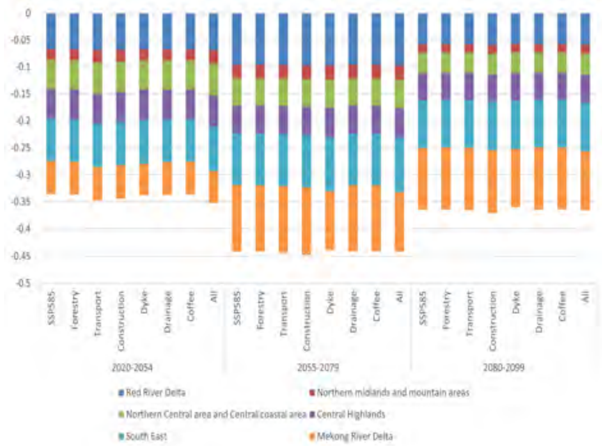


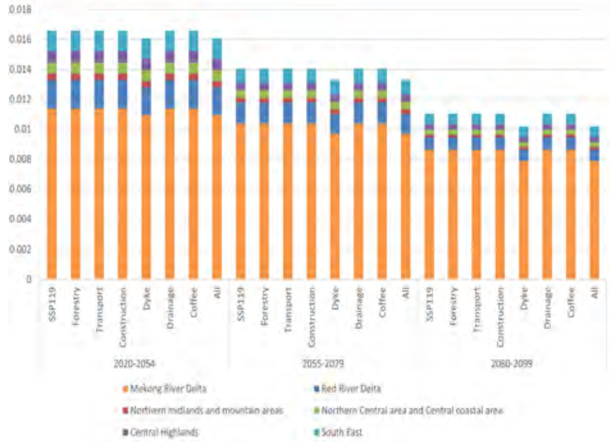


Source: own computation.

Figure 22: Damages and value added fruit tree (in percent relative to GDP in the Baseline)

Damage | Value added

SSP119



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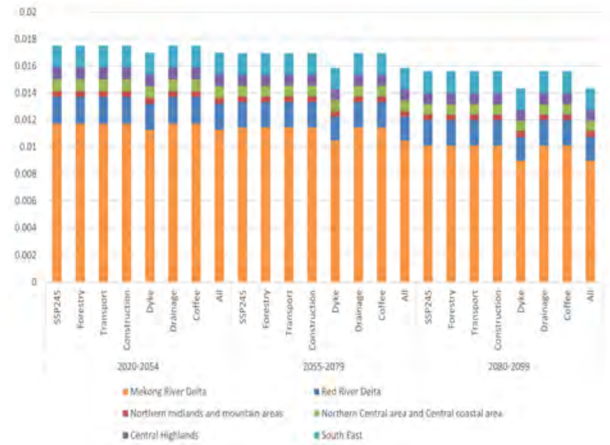

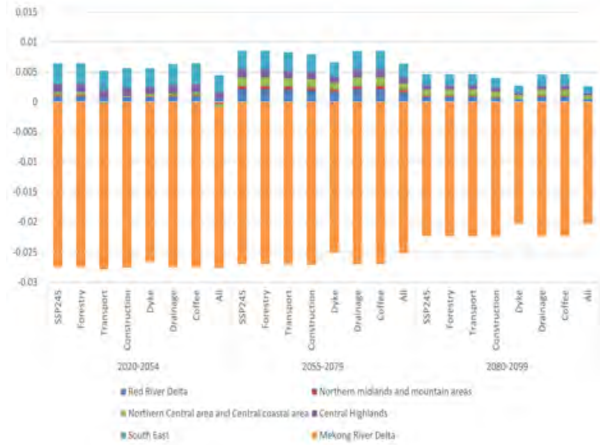

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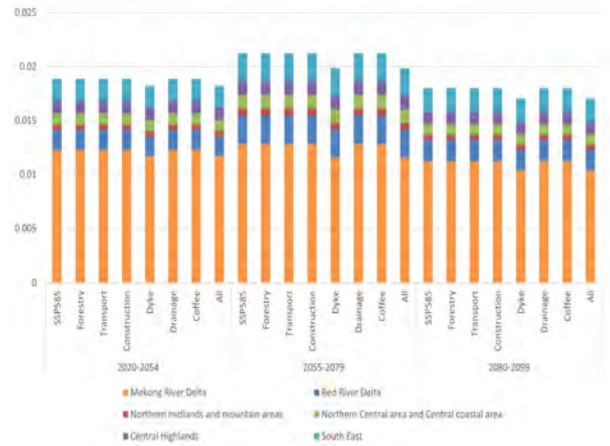
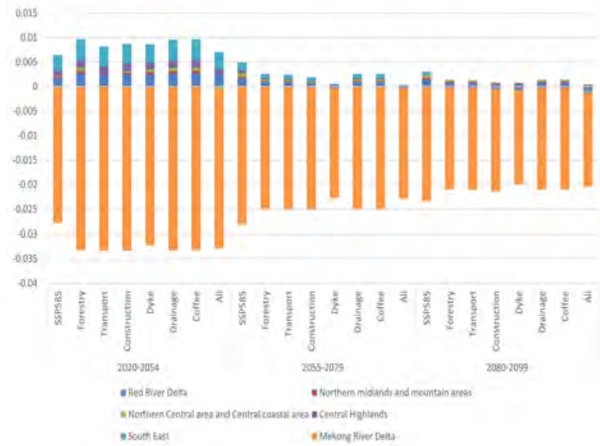


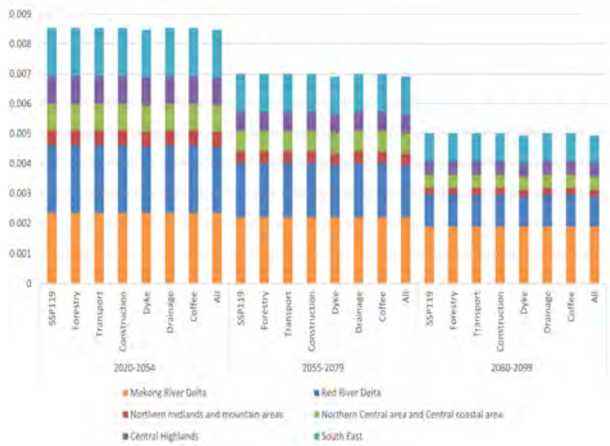


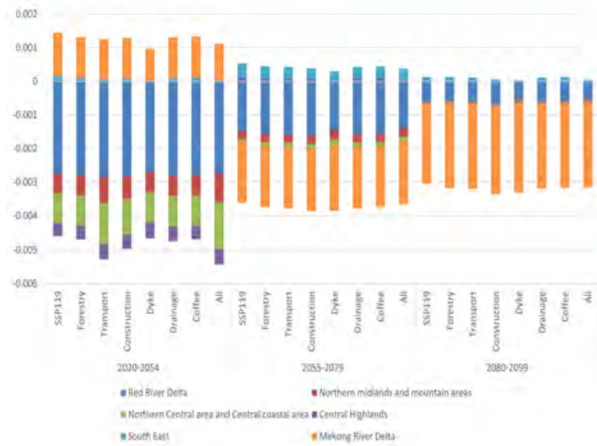
Source: own computation.

Figure 23: Damages and value added dry rubber (in percent relative to GDP in the Baseline)

Damage | Value added

SSP119





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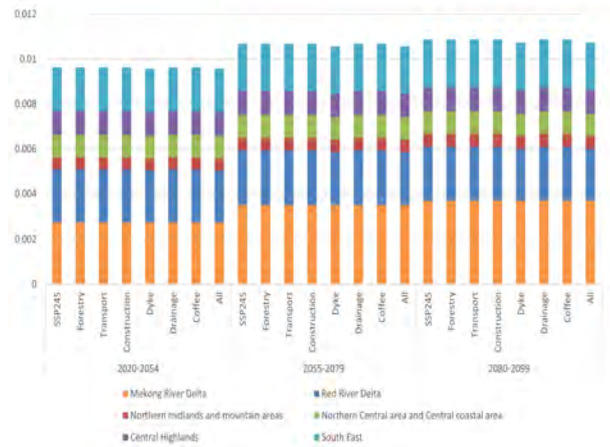

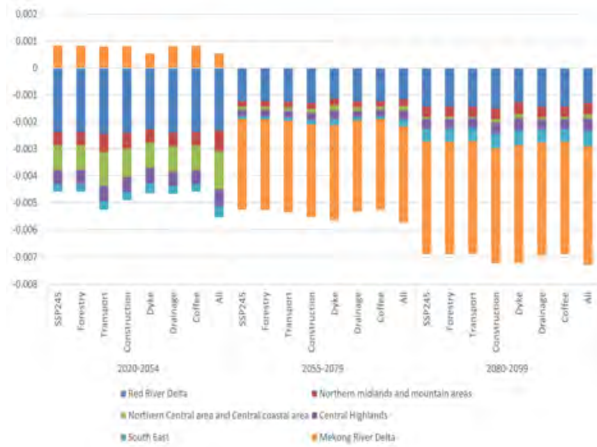

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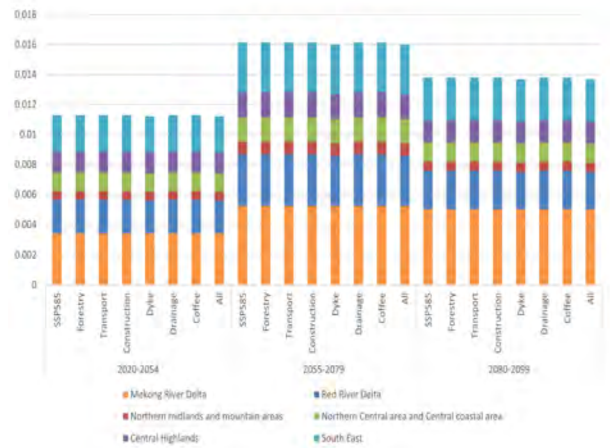
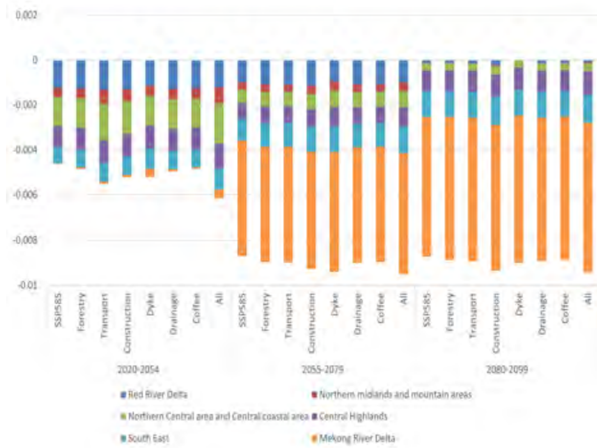


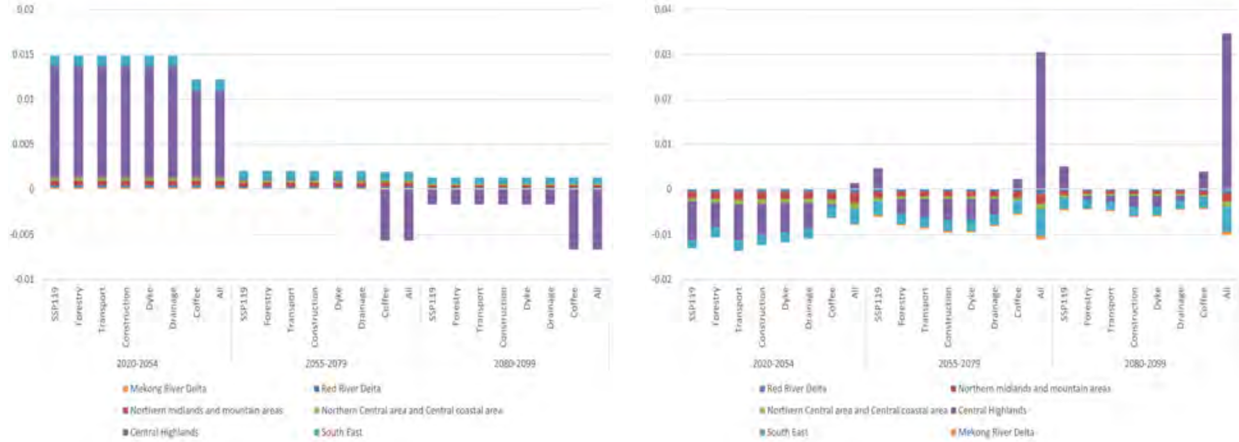


Source: own computation.

Figure 24: Damages and value added coffee (in percent relative to GDP in the Baseline)

Damage | Value added

SSP119



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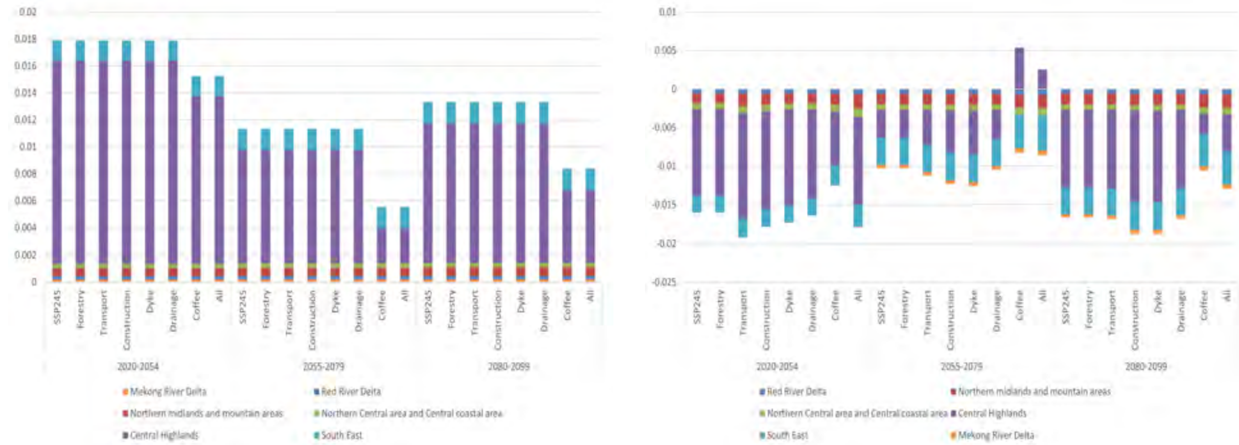

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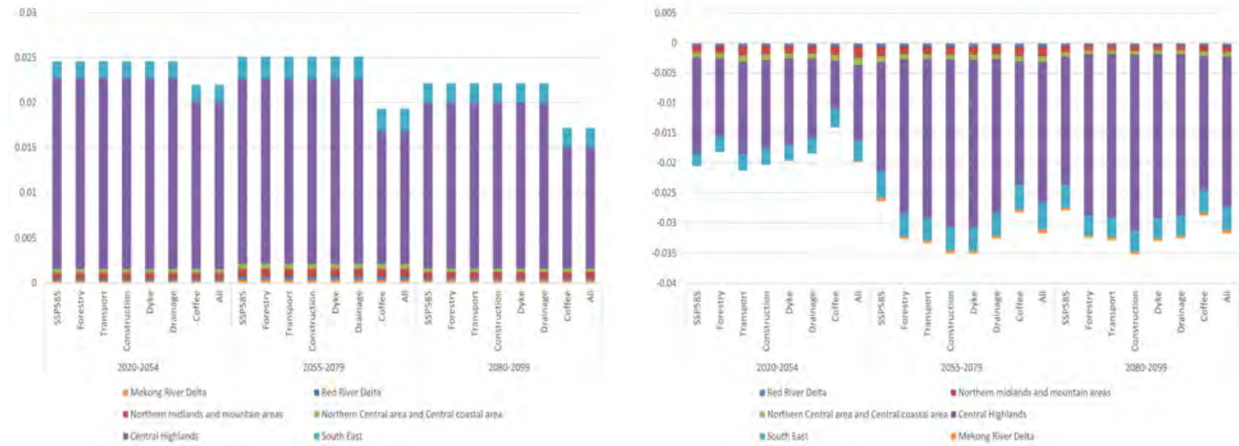
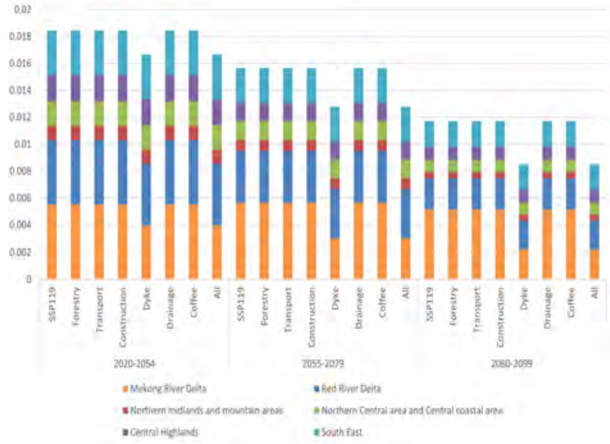


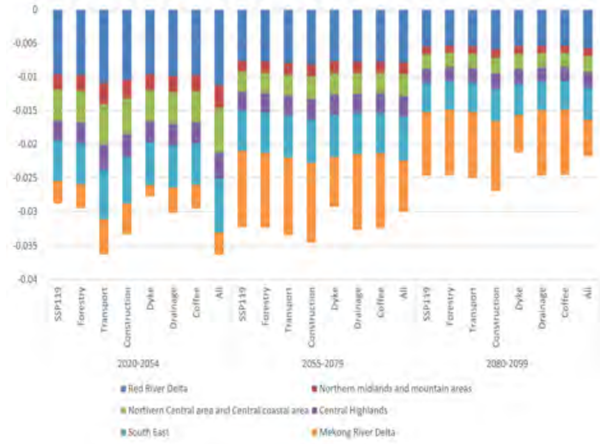
Source: own computation.

Figure 25: Damages and value added other perennial crops (in percent relative to GDP in the Baseline)

Damage | Value added

SSP119





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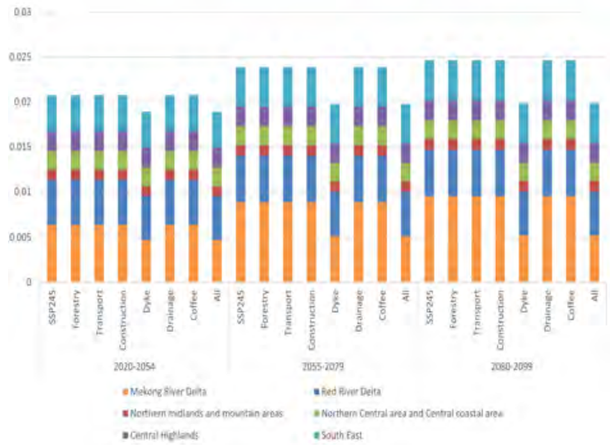

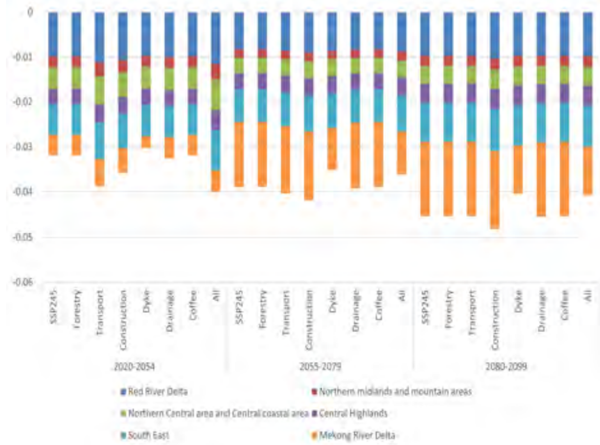

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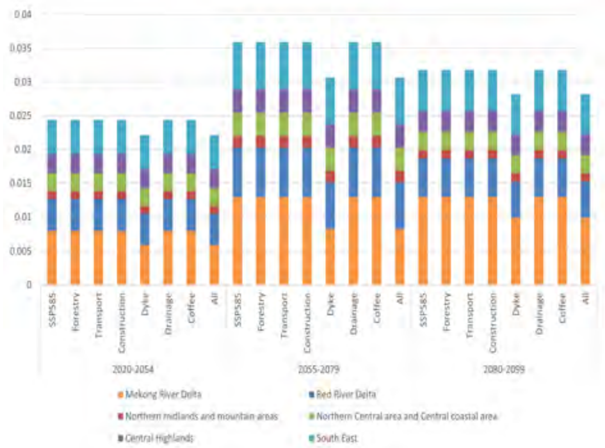
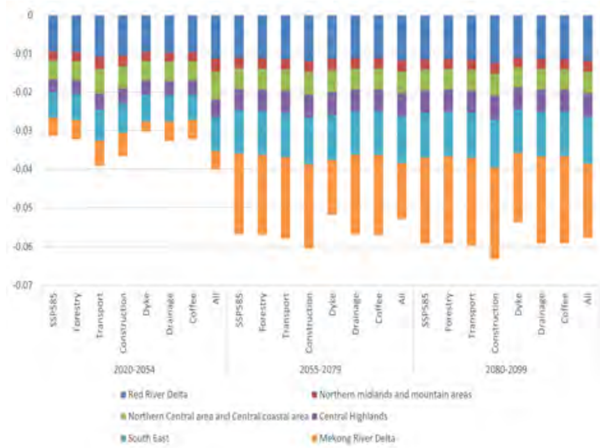




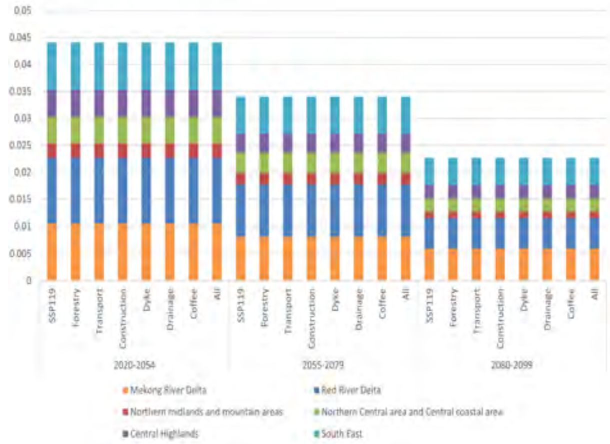
Source: own computation.

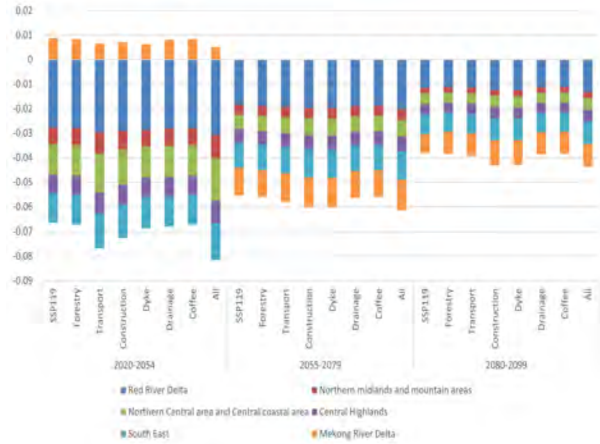
Figure 26: Damages and value added live stock and agricultural services (in percent relative to GDP in the Baseline)

Damage

Value added

SSP119





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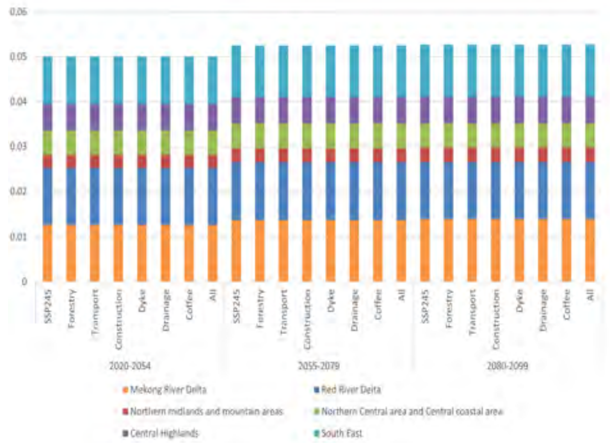

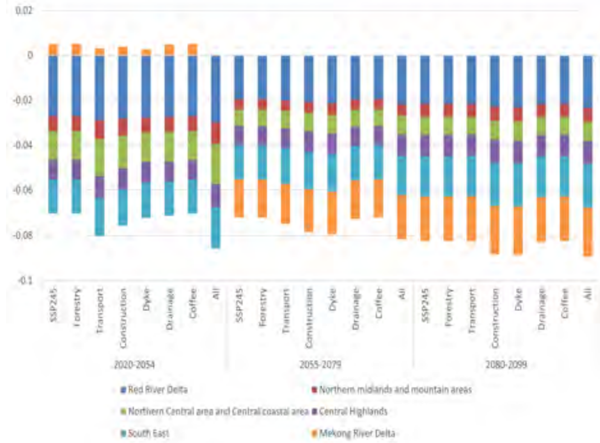

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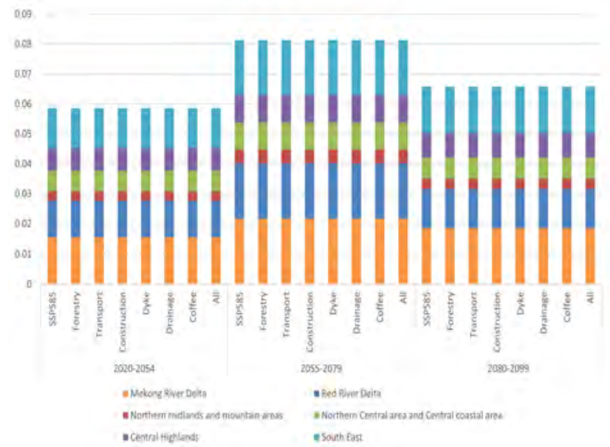
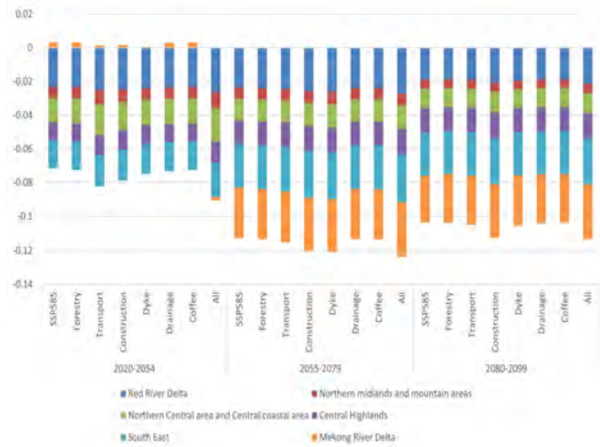


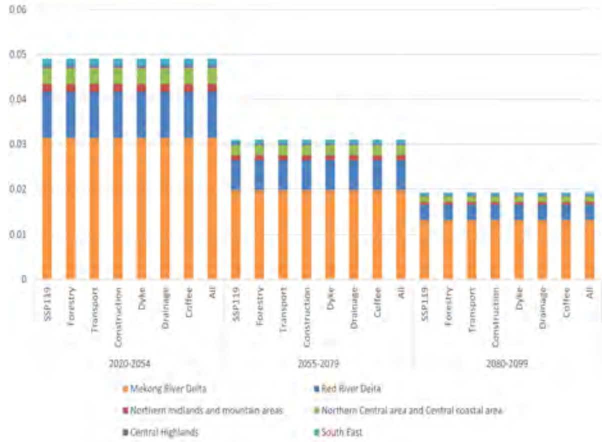


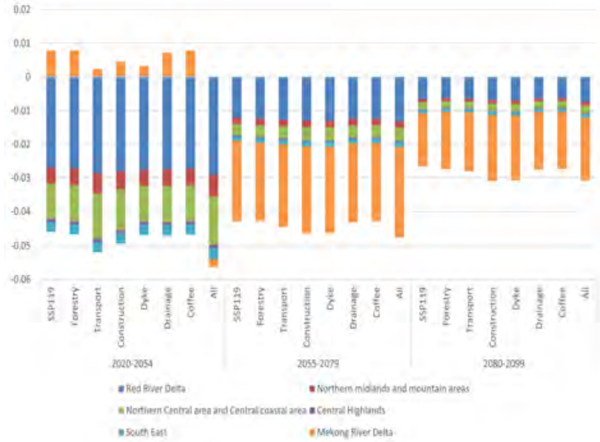
Source: own computation.

Figure 27: Damages and value added aquaculture (in percent relative to GDP in the Baseline)

Damage | Value added

SSP119





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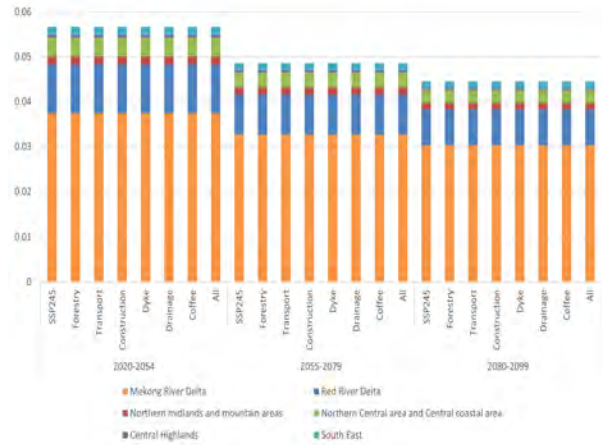

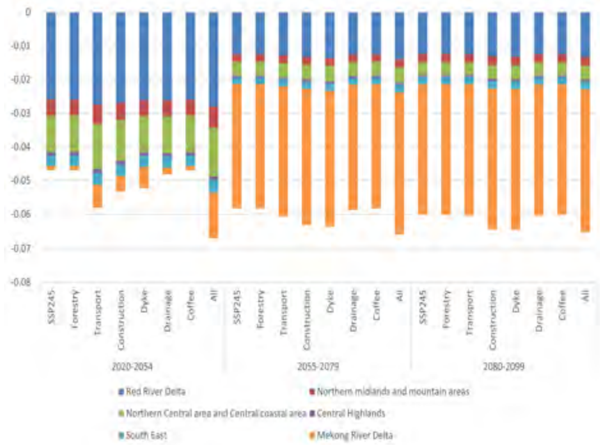

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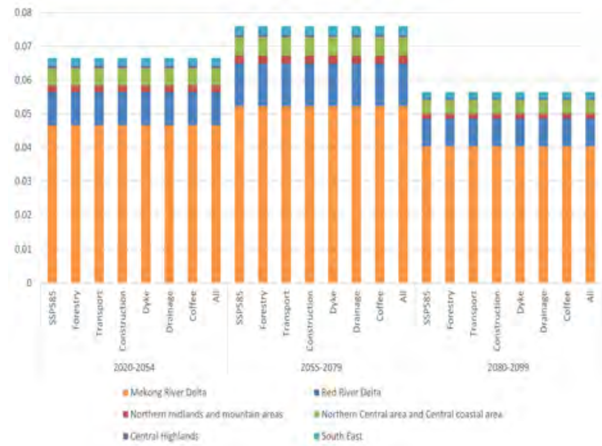
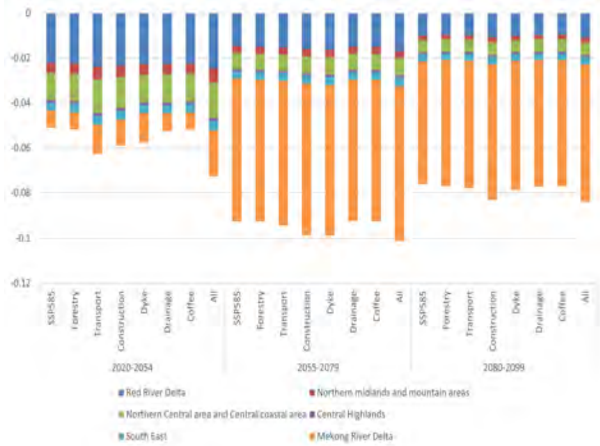


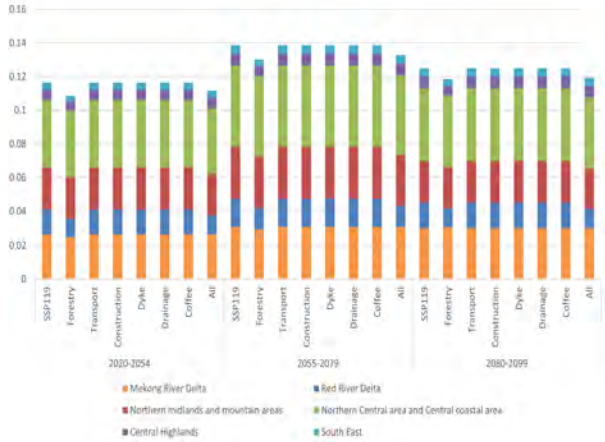


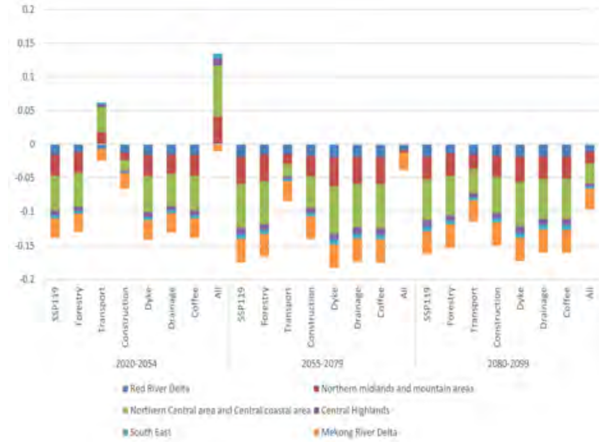
Source: own computation.

Figure 28: Damages and value added forestry (in percent relative to GDP in the Baseline)

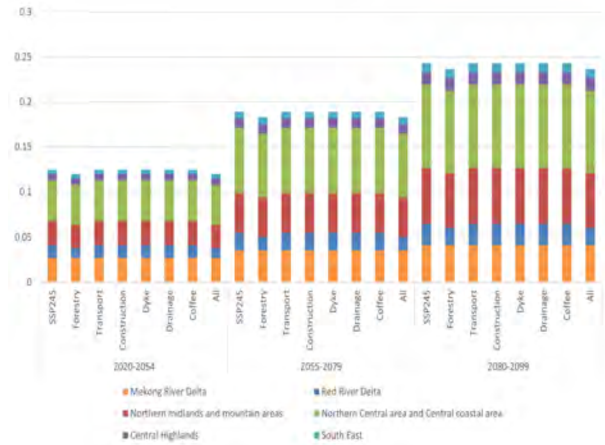
Damage | Value added

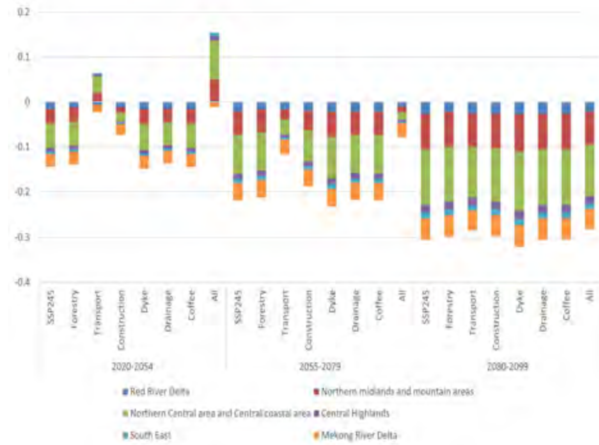
SSP119



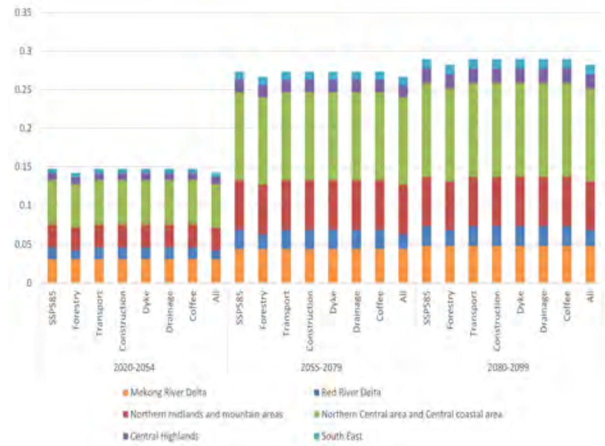


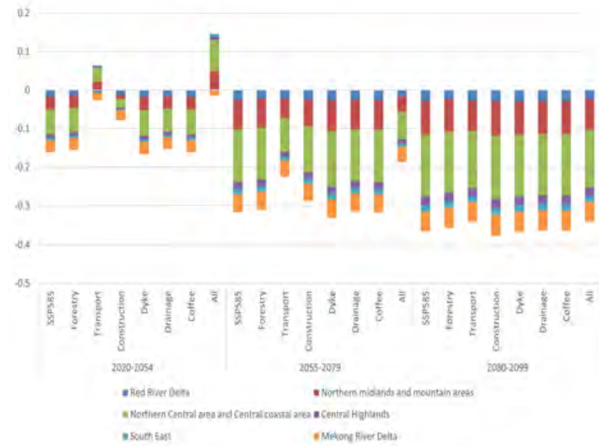
SSP245





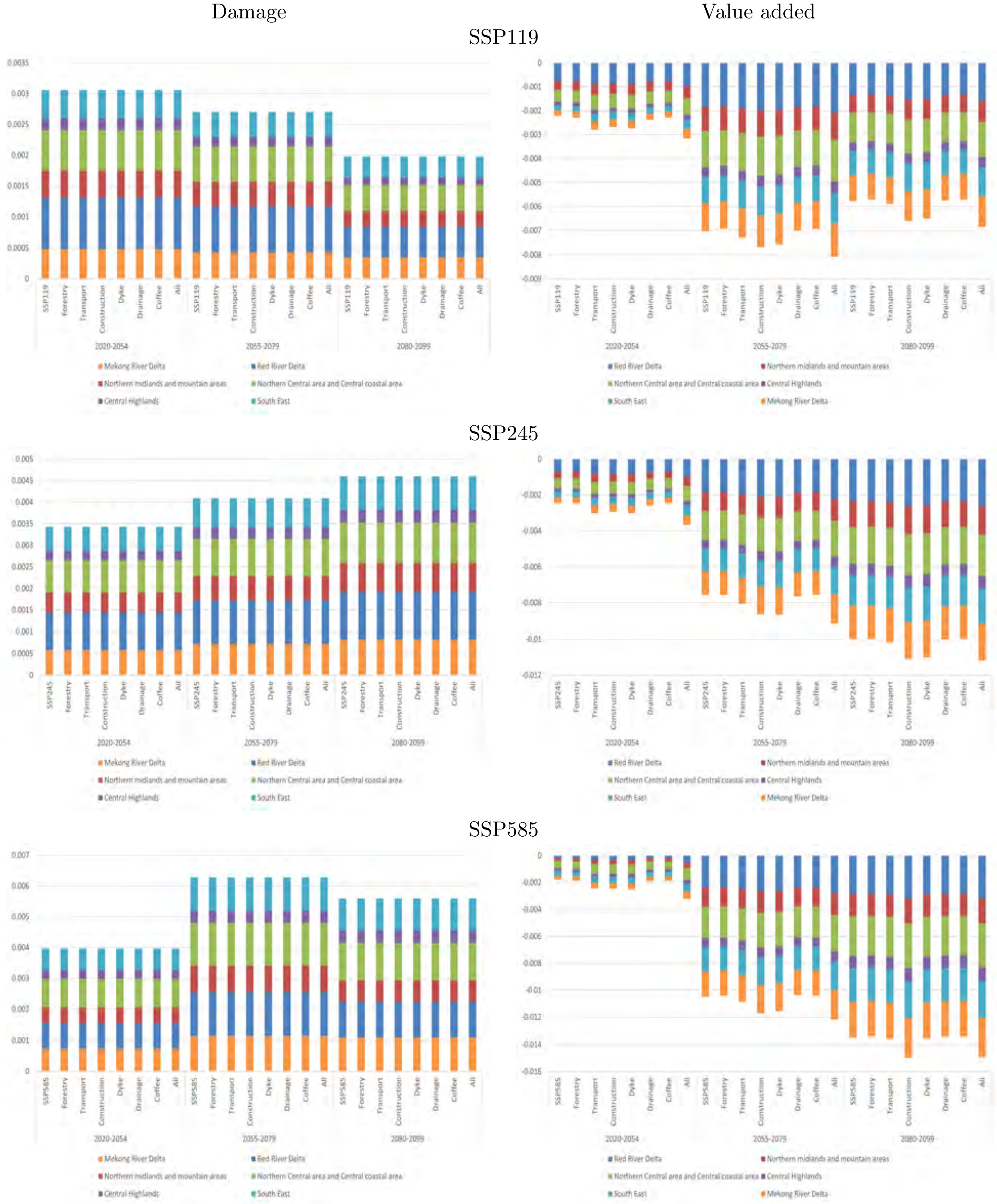
SSP585





Source: own computation.

Figure 29: Damages and value added water (in percent relative to GDP in the Baseline)

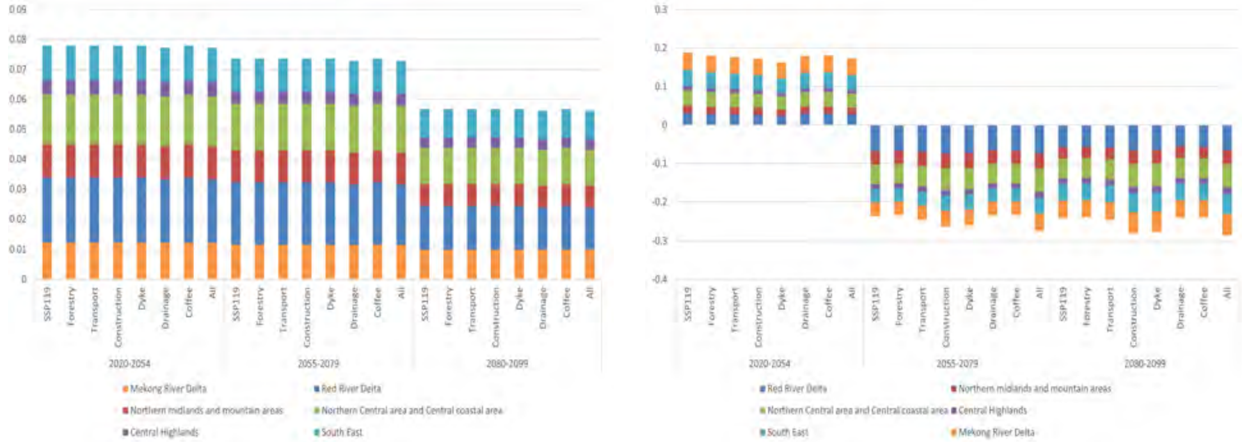


Source: own computation.

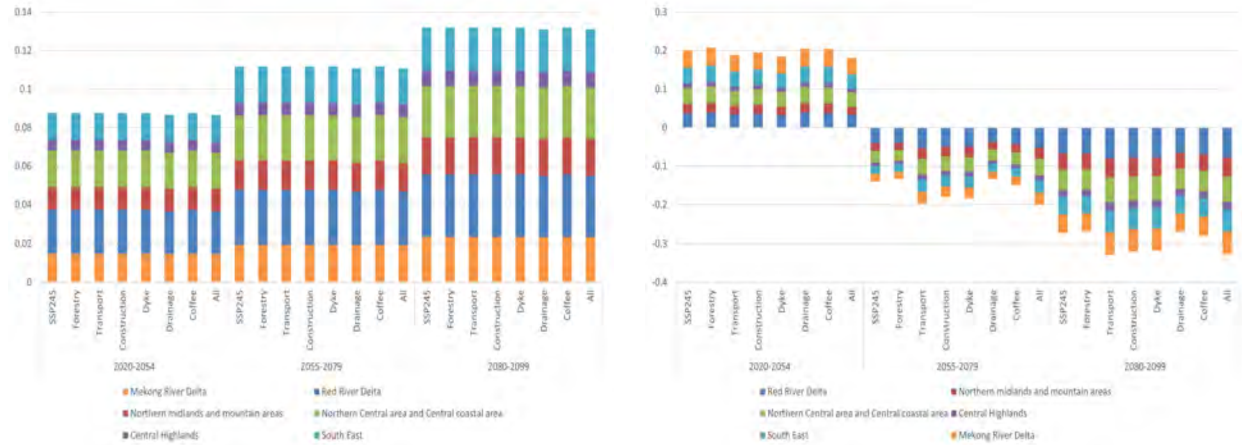
Figure 30: Damages and value added energy (in percent relative to GDP in the Baseline)

Damage Value added

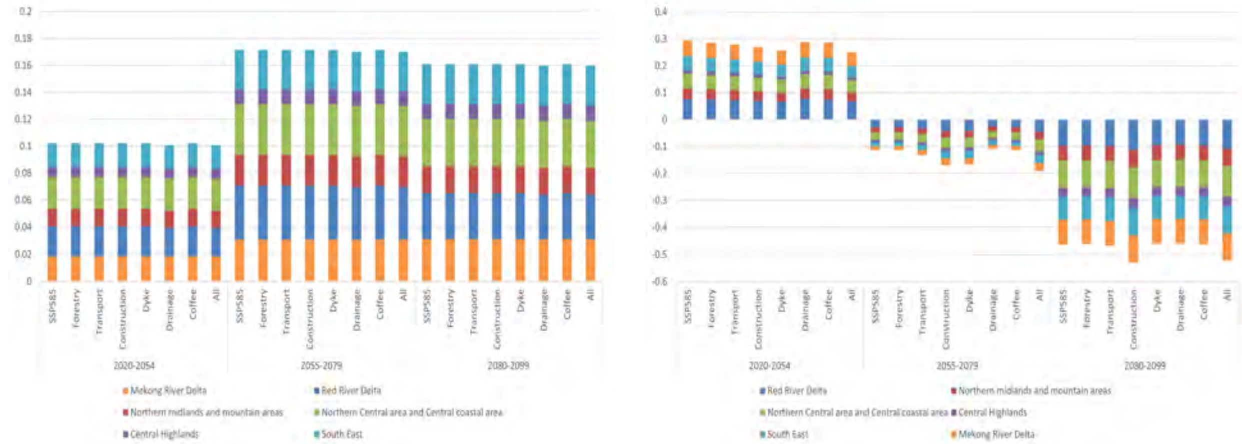
SSP119



SSP245



SSP585

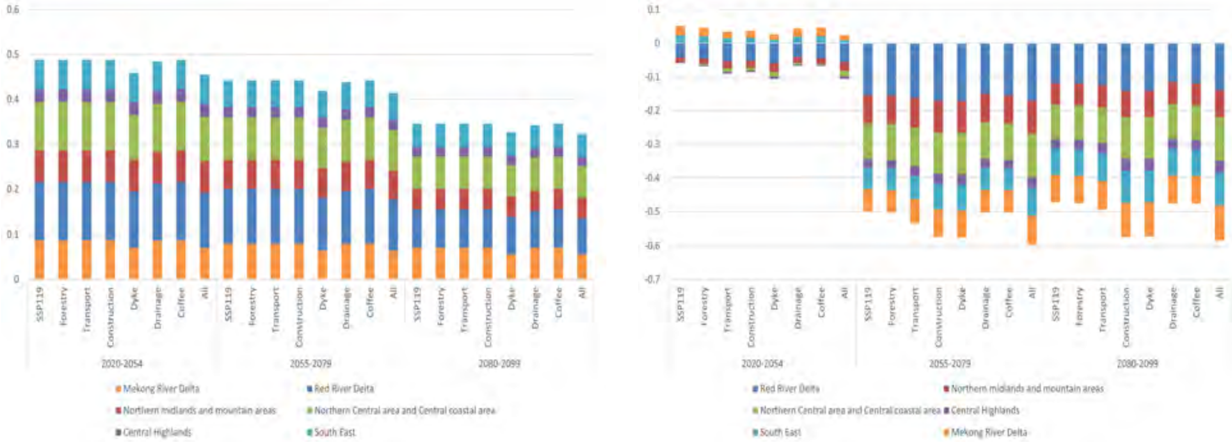


Source: own computation.

Figure 31: Damages and value added manufacturing (in percent relative to GDP in the Baseline)

Damage | Value added

SSP119



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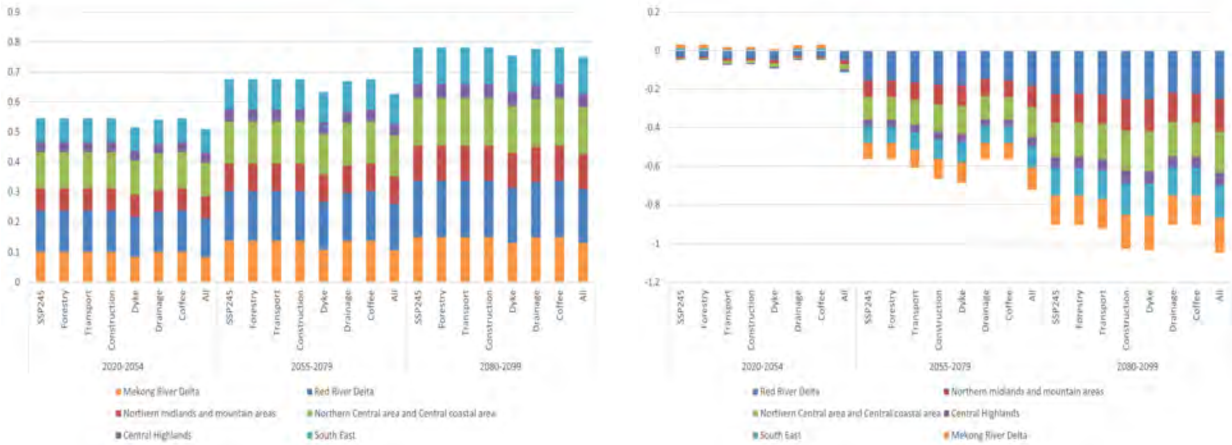
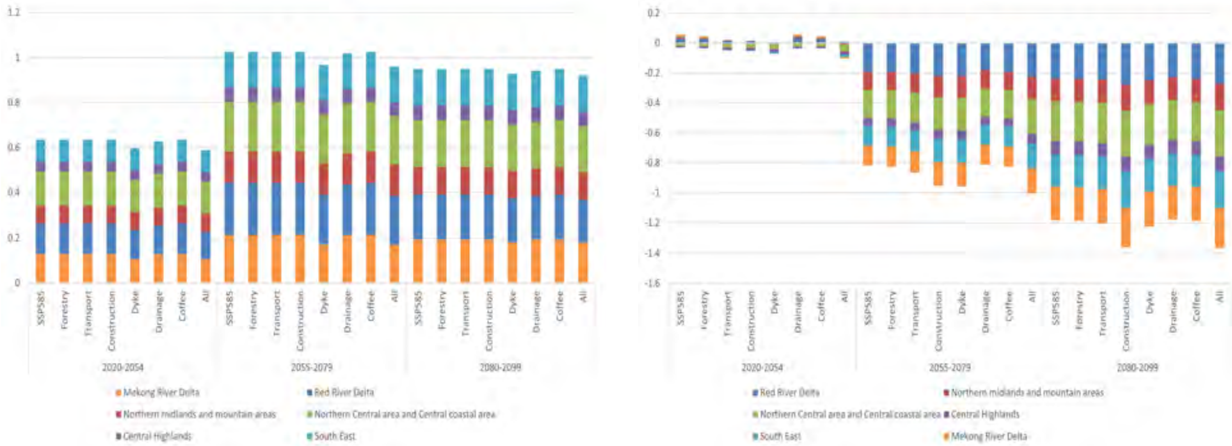


SSP585

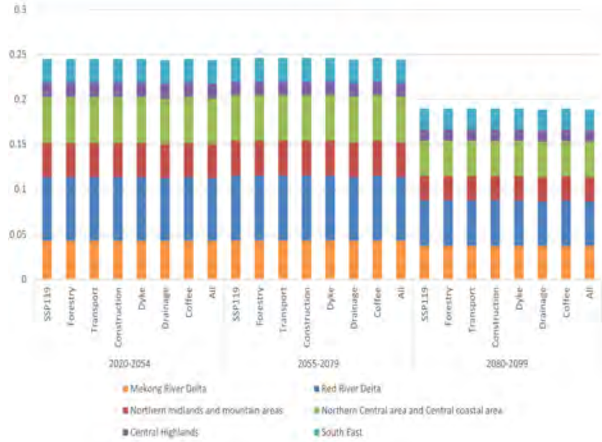


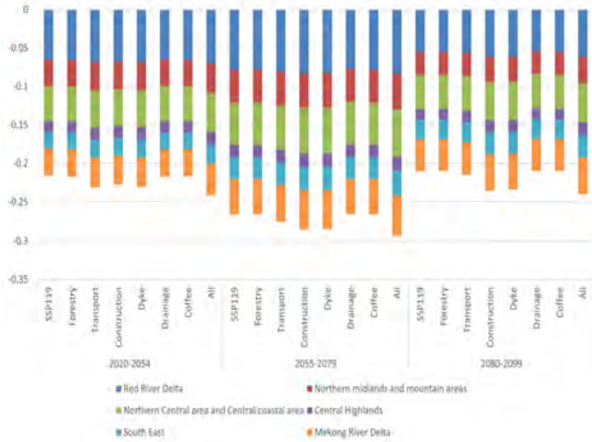
Source: own computation.

Figure 32: Damages and value added construction (in percent relative to GDP in the Baseline)

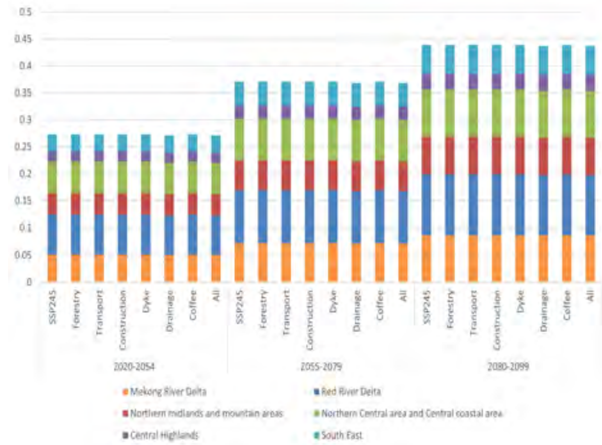
Damage | Value added

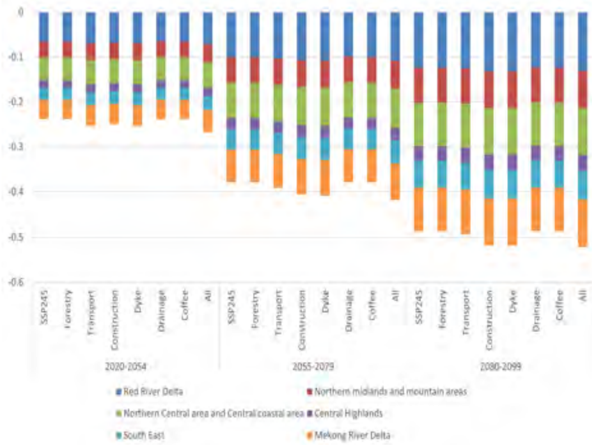
SSP119





SSP245





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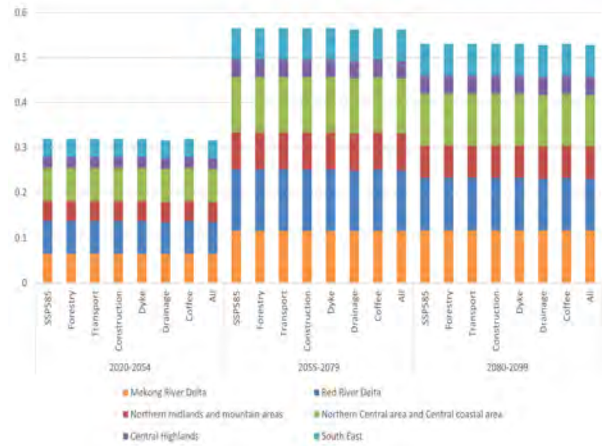
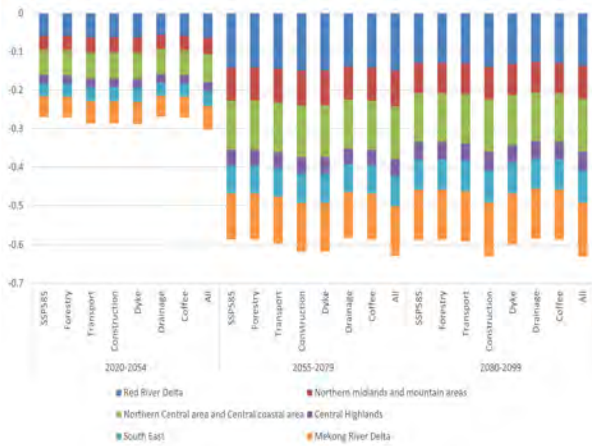


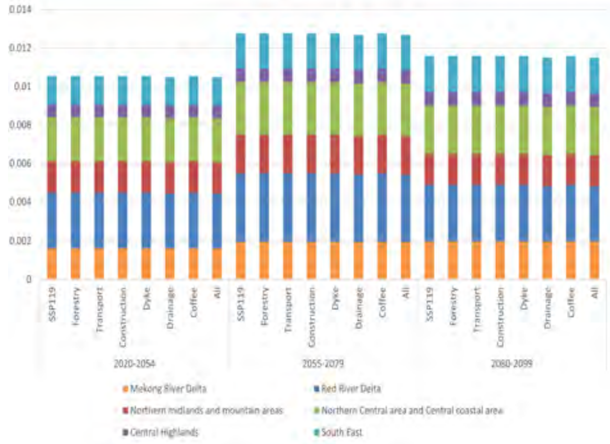


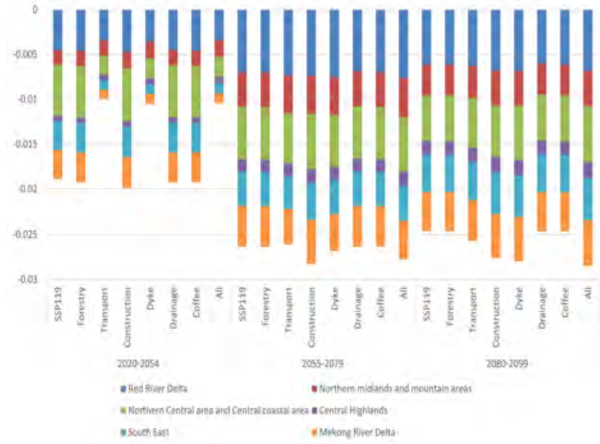
Source: own computation.

Figure 33: Damages and value added transport water (in percent relative to GDP in the Baseline)

Damage | Value added

SSP119





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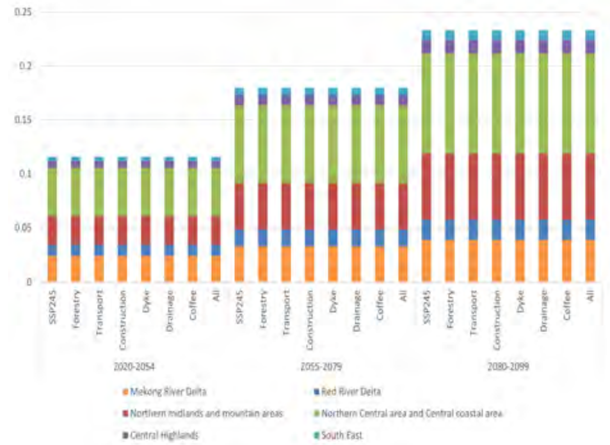
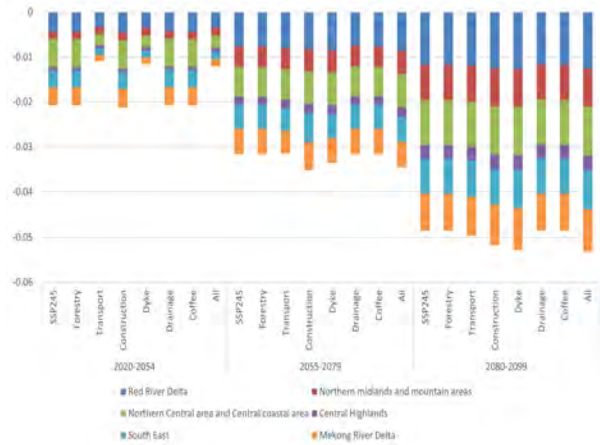
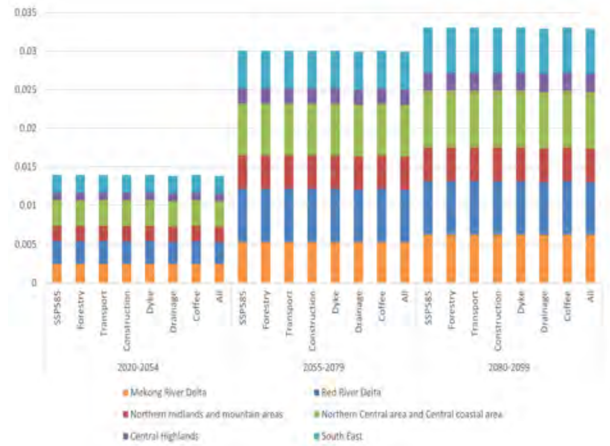
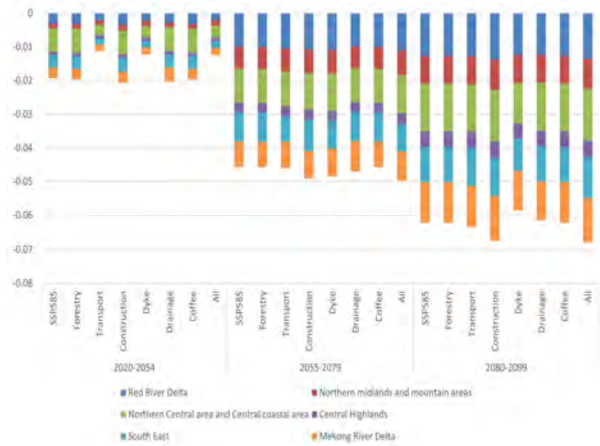




SSP585



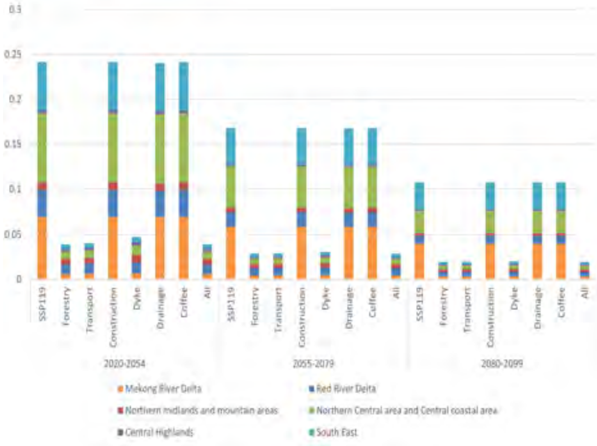


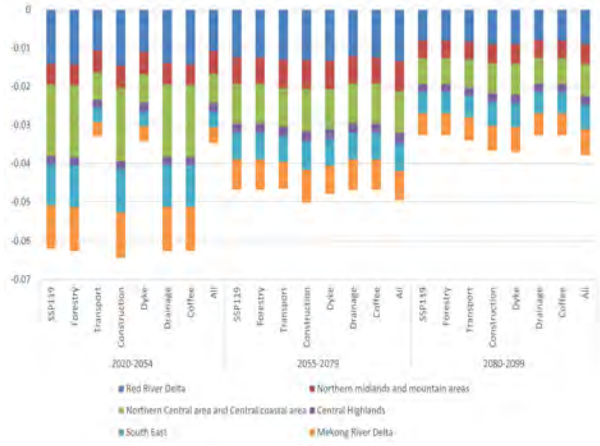
Source: own computation.

Figure 34: Damages and value added transport land (in percent relative to GDP in the Baseline)

Damage | Value added

SSP119





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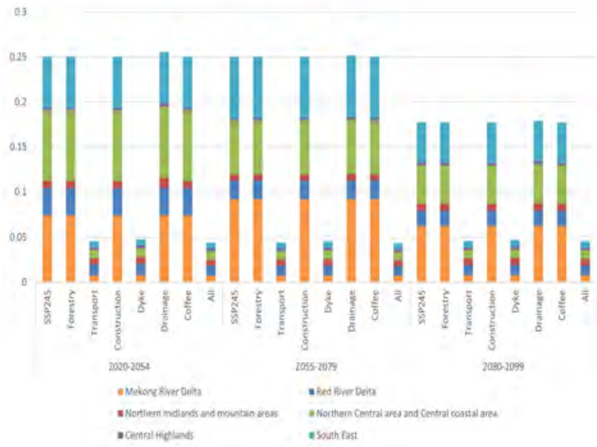
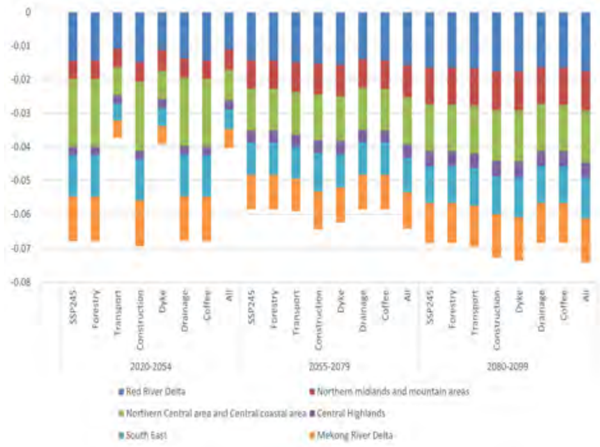
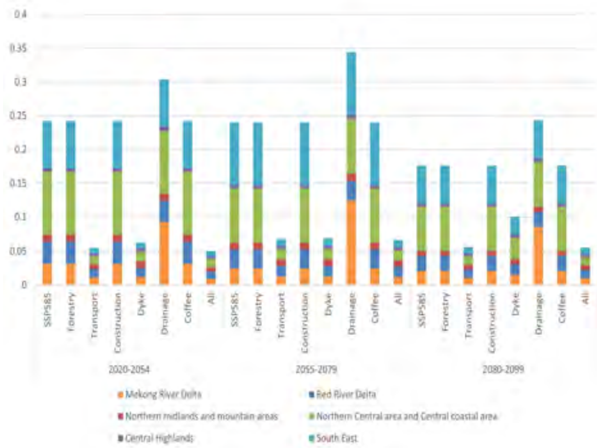
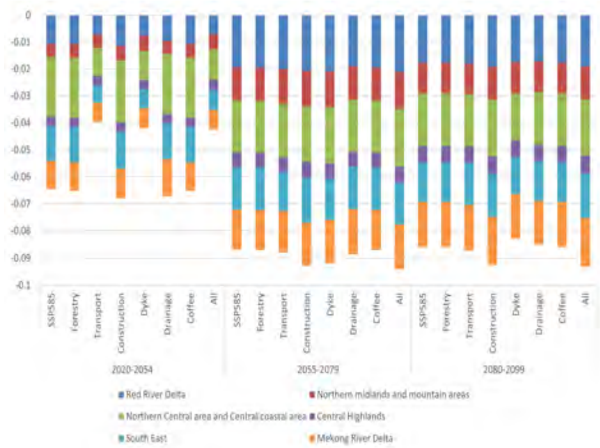




SSP585



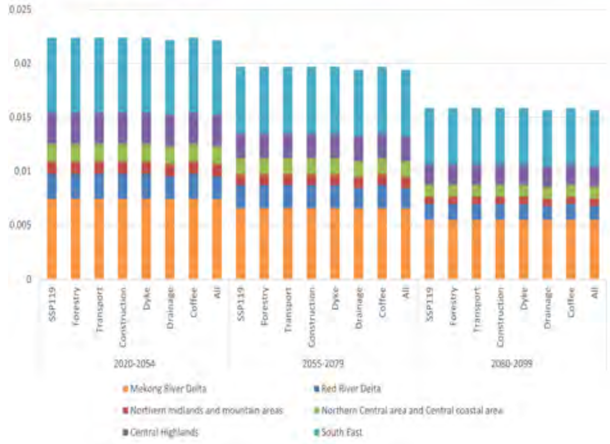


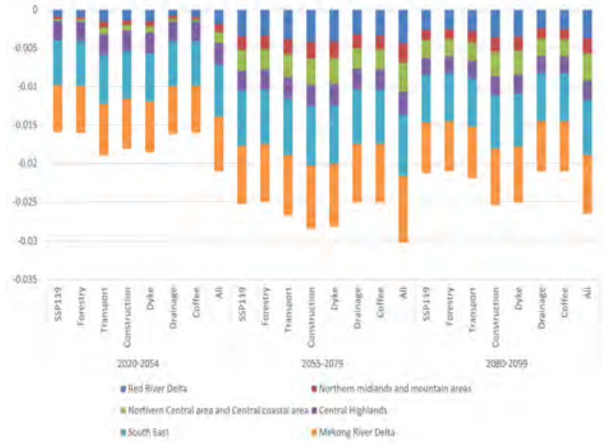
Source: own computation.

Figure 35: Damages and value added health (in percent relative to GDP in the Baseline)

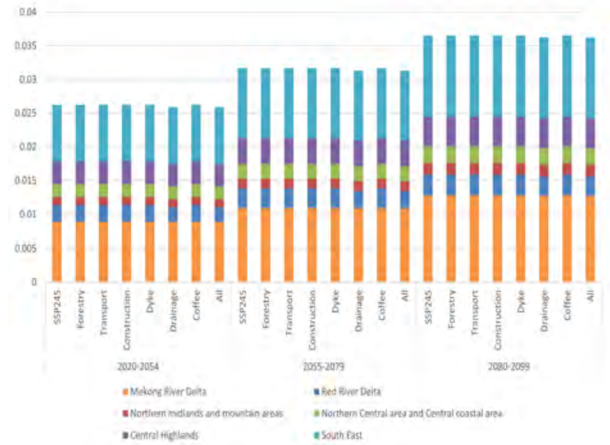
Damage | Value added

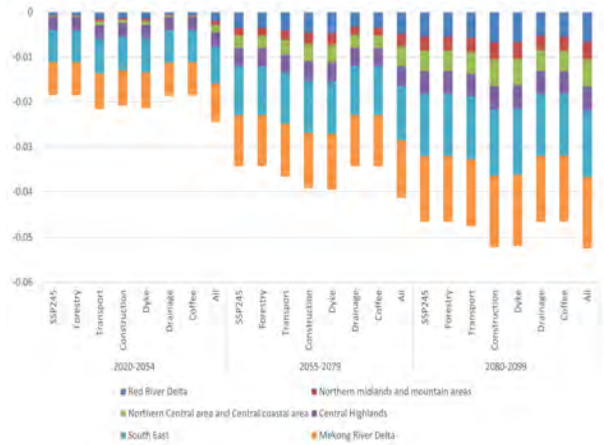
SSP119



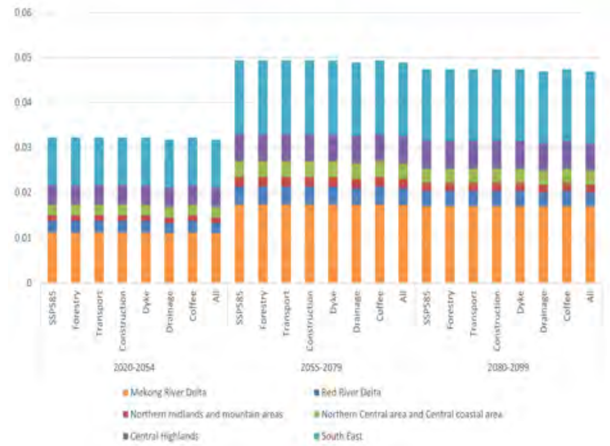


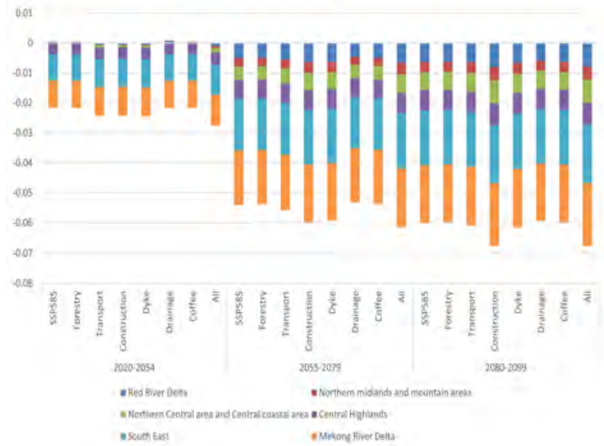
SSP245





SSP585



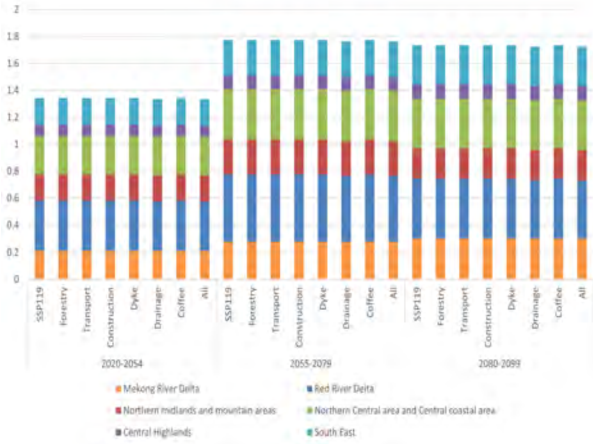


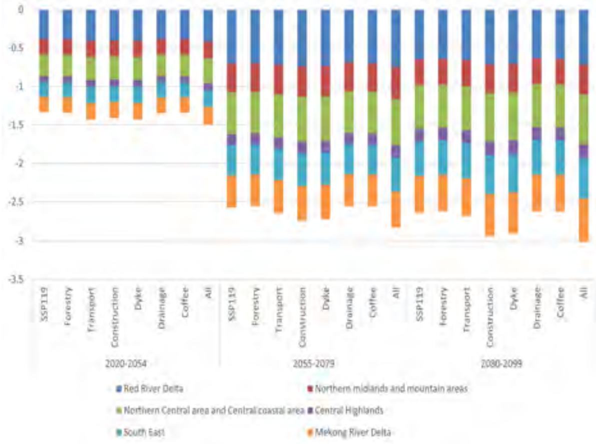
Source: own computation.

Figure 36: Damages and value added services (in percent relative to GDP in the Baseline)

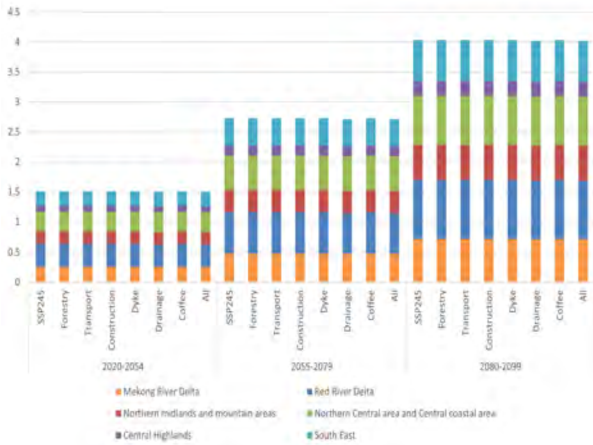
Damage | Value added

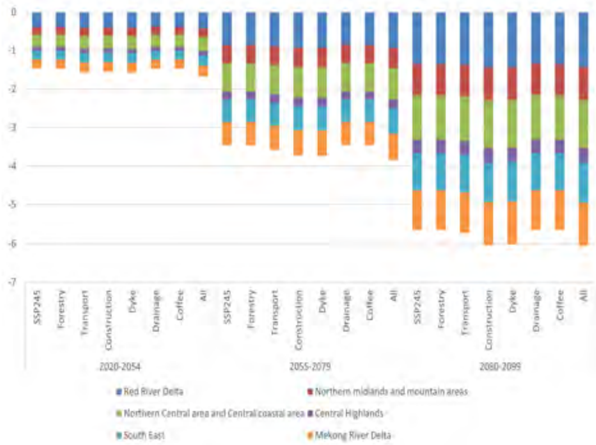
SSP119





SSP245





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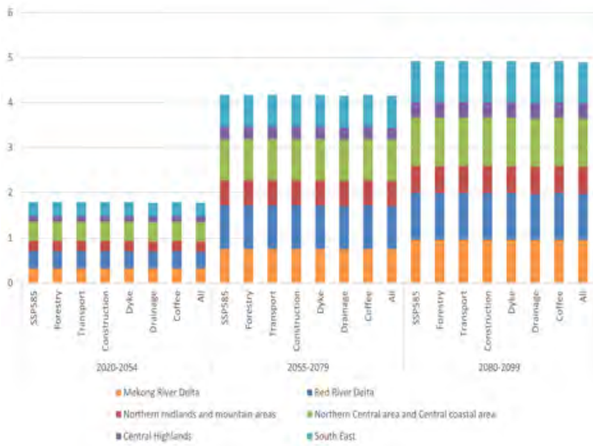
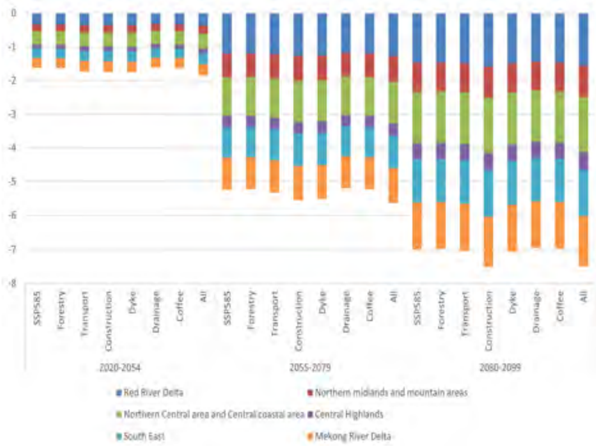
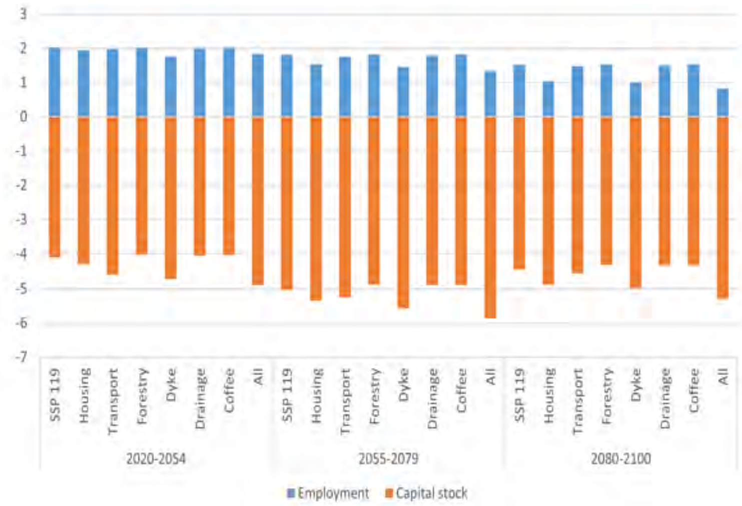


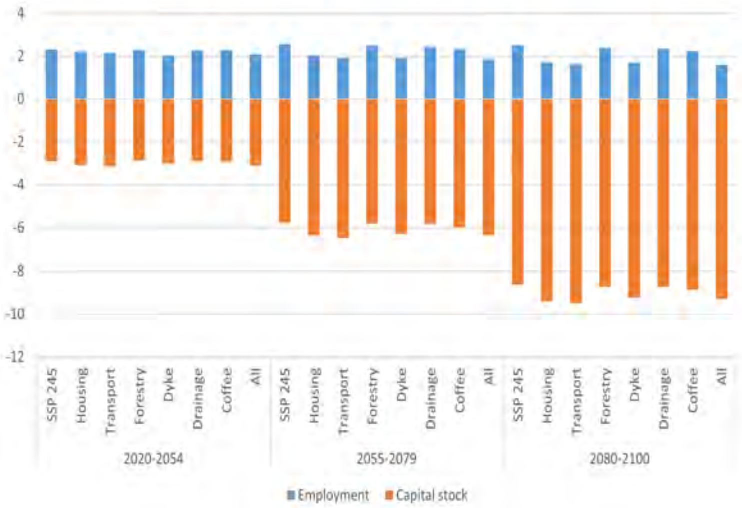


Source: own computation.

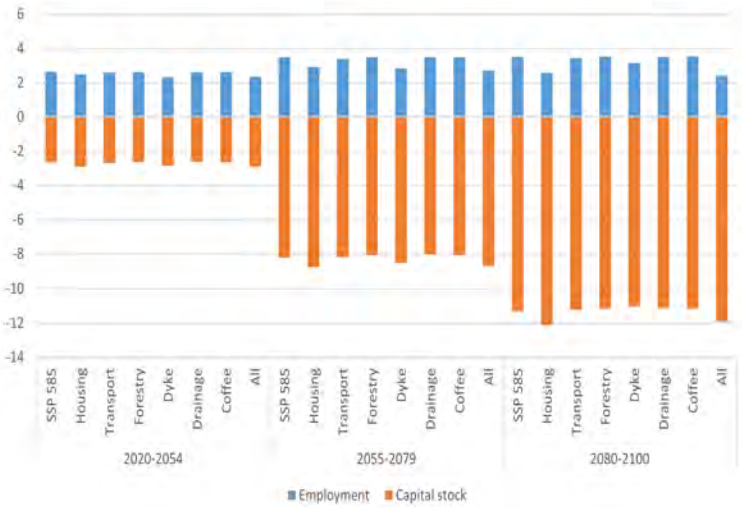
Figure 37: Primary production factors (in percent relative to Baseline scenario)



PrimaryFactors.jpg



PrimaryFactors.jpg



PrimaryFactors.jpg

Source: own computation.

B Tables

Table 19: Regional climate variable

Region	Red River Delta	Northern midlands and mountain areas	Northern Central area and Central coastal area	Central Highlands	South East	Mekong River Delta
initial surface temperature (Celsius) (tas)	20.85	18.55	22.86	22.26	25.64	26.27
initial surface windspeed (m/s) (SfcWind)	2.67	2.04958	3.39	1.96	2.276182	3.21
initial surface precipitation flux (mm) (pr)	1235.71	1322.53	2244.48	2638.4	2743.77	2701.13
initial sunshine (hour per day) (sunshine)	0	0	0	0	0	0
initial surface relative humidity (percent) (hurs)	83.84	85.10	88.02	89.54	84.48	85.74
initial heatwaves per year (heatwave)	0	0	0	0	0	0
initial maximal consecutive dry days (maxdrydays)	25.18	28.64	13.5	18.20	30.33	15.07
initial maximal consecutive wet days (maxwetdays)	12.09	16.35	25.86	67.20	56.16	39.77
initial number of storms (eq. to avg. historic storm) (storms)	0	0	0	0	0	0
initial number of floods (eq. to historic floods) (floods)	0	0	0	0	0	0
initial number of forest fire (fire) (fire)	0	0	0	0	0	0
initial landslide (landslide)	0	0	0	0	0	0

Source: National expert computation based on results from an NOAA.

Table 20: Mapping of economic sectors

Aggregate sector	Sub-sector	Commodity group	Industry Group
Basics (1)	Rice (1)	1	1
Basics (1)	Other annual crops (2)	2-8	2-8
Basics (1)	Fruit tree (3)	9	9
Basics (1)	Dry rubber (4)	12	12
Basics (1)	Coffee (5)	13	13
Basics (1)	Other perennial crops (6)	10-11, 14-15	10-11, 14-15
Basics (1)	Live stock and agricultural services (7)	16-21	16-21
Basics (1)	Aquaculture (8)	26-27	26-27
Basics (1)	Forestry (9)	22-25	22-25
Basics (1)	Water (10)	101-102	105-106
Basics (1)	Energy (11)	28-30, 99-100	28-30, 99-104
Construction and Manufacturing (2)	Manufacturing (7)	31-97	31-97
Construction and Manufacturing (2)	Construction (8)	106-111	110-115
Transport Water (3)	Transport Water (9)	119-120	123-124
Transport Land (4)	Transport Land (10)	115-118, 121-122	119-122, 125-126
Services and Health (5)	Health (11)	154-155	157-158
Services and Health (5)	Services (12)	98, 103-105, 112-114, 123-153, 156-164	98, 107-109, 116-118, 127-156, 159-168

Table 21: Mapping of provinces to statistical regions in Vietnam

Region	Province
Dak Nong	Central Highlands
Dak Lak	Central Highlands
Gia Lai	Central Highlands
Kon Tum	Central Highlands
Lam Dong	Central Highlands
Dong Thap	Mekong River Delta
An Giang	Mekong River Delta
Bac Lieu	Mekong River Delta
Ben Tre	Mekong River Delta
Ca Mau	Mekong River Delta
Can Tho	Mekong River Delta
Hau Giang	Mekong River Delta
Kien Giang	Mekong River Delta

Table 21 – Continued

Region	Province
Long An	Mekong River Delta
Soc Trang	Mekong River Delta
Tien Giang	Mekong River Delta
Tra Vinh	Mekong River Delta
Vinh Long	Mekong River Delta
Da Nang	Northern Central area and Central coastal area
Binh Dinh	Northern Central area and Central coastal area
Binh Thuan	Northern Central area and Central coastal area
Ha Tinh	Northern Central area and Central coastal area
Khanh Hoa	Northern Central area and Central coastal area
Nghe An	Northern Central area and Central coastal area
Ninh Thuan	Northern Central area and Central coastal area
Phu Yen	Northern Central area and Central coastal area
Quang Binh	Northern Central area and Central coastal area
Quang Nam	Northern Central area and Central coastal area
Quang Ngai	Northern Central area and Central coastal area
Quang Tri	Northern Central area and Central coastal area
Thua Thien-Hue	Northern Central area and Central coastal area
Thanh Hoa	Northern Central area and Central coastal area
Dien Bien	Northern midlands and mountain areas
Bac Giang	Northern midlands and mountain areas
Bac Kan	Northern midlands and mountain areas
Cao Bang	Northern midlands and mountain areas
Ha Giang	Northern midlands and mountain areas
Hoa Binh	Northern midlands and mountain areas
Lao Cai	Northern midlands and mountain areas
Lai Chau	Northern midlands and mountain areas
Lang Son	Northern midlands and mountain areas
Phu Tho	Northern midlands and mountain areas
Son La	Northern midlands and mountain areas
Thai Nguyen	Northern midlands and mountain areas
Tuyen Quang	Northern midlands and mountain areas
Yen Bai	Northern midlands and mountain areas
Bac Ninh	Red River Delta
Ha Noi	Red River Delta
Ha Nam	Red River Delta
Hung Yen	Red River Delta
Hai Duong	Red River Delta
Hai Phong	Red River Delta
Nam Dinh	Red River Delta
Ninh Binh	Red River Delta
Quang Ninh	Red River Delta
Thai Binh	Red River Delta
Vinh Phuc	Red River Delta
Dong Nai	South East
Ba Ria - Vung Tau	South East
Binh Duong	South East
Binh Phuoc	South East
Ho Chi Minh city	South East
Tay Ninh	South East

Table 22: Housing adaptation measures against sea-level rise

SLR in cm	Red River Delta	Northern midland and mountain area	Northern Central area and Central coastal area	Central Highlands	South East	Mekong River Delta	Vietnam
			Benefit (avoided Damage)				
0	0.000298	0	0.000678	0	0	0.042223	0.0432
5	0.000772	0	0.001244	0	0.000179	0.077075	0.079269
10	0.002181	0	0.002706	0	0.000427	0.180979	0.186294
15	0.003752	0	0.0036	0	0.000819	0.28184	0.290011
20	0.005487	0	0.00459	0	0.001384	0.480361	0.491822
25	0.006701	0	0.005551	0	0.002214	0.502044	0.51651
30	0.007981	0	0.007021	0	0.003172	0.536664	0.554837
35	0.00934	0	0.008066	0	0.004192	0.574884	0.596483
40	0.010845	0	0.009317	0	0.005259	0.633413	0.658833
45	0.01258	0	0.010851	0	0.00628	0.704784	0.734494
50	0.014408	0	0.012154	0	0.007289	0.811796	0.845647
55	0.016436	0	0.013557	0	0.008281	0.927106	0.96538
60	0.018669	0	0.014995	0	0.009255	1.035385	1.078304
65	0.021082	0	0.0165	0	0.010276	1.127374	1.175232
70	0.02363	0	0.018013	0	0.011302	1.249021	1.301966
75	0.02633	0	0.019747	0	0.01245	1.359061	1.417588
80	0.029257	0	0.021546	0	0.013644	1.469071	1.533518
85	0.032306	0	0.023341	0	0.015039	1.558247	1.628933
90	0.035366	0	0.025083	0	0.01636	1.637068	1.713877
95	0.038634	0	0.035527	0	0.024139	1.696292	1.794592
			Cost (to avoid Damage)				
0	0.003068	0	0.006946	0	0	0.435775	0.445789
5	0.004871	0	0.005788	0	0.001843	0.35969	0.372192
10	0.014506	0	0.014976	0	0.002556	1.072371	1.10441
15	0.016163	0	0.009152	0	0.004043	1.040948	1.070306
20	0.017852	0	0.010129	0	0.005826	2.048878	2.082685
25	0.012483	0	0.00984	0	0.008561	0.223789	0.254673
30	0.013177	0	0.015049	0	0.009869	0.357298	0.395392
35	0.013984	0	0.010708	0	0.010523	0.394463	0.429678
40	0.015477	0	0.012806	0	0.010999	0.604056	0.643338
45	0.017852	0	0.0157	0	0.010523	0.736607	0.780682
50	0.018814	0	0.013349	0	0.010404	1.104432	1.146999
55	0.020862	0	0.014361	0	0.010226	1.190088	1.235537
60	0.022975	0	0.014723	0	0.010047	1.117512	1.165258
65	0.024827	0	0.015411	0	0.010523	0.949391	1.000151
70	0.026223	0	0.015483	0	0.010582	1.255486	1.307774
75	0.027773	0	0.017762	0	0.011831	1.135696	1.193061
80	0.030122	0	0.018413	0	0.012306	1.135377	1.196219
85	0.031371	0	0.018377	0	0.014387	0.92036	0.984495
90	0.031485	0	0.017834	0	0.013614	0.81349	0.876424
95	0.033623	0	0.106933	0	0.0802	0.611234	0.83199

Source: Nam, Long, Sam, Hai & Hai (2021) and own computation.

Table 23: Housing adaptation measures against storms

Year after Start	Red River Delta	Northern midland and mountain area	Northern Central area and Central coastal area	Central Highlands	South East	Mekong River Delta	Vietnam
			Benefit (avoided Damage)				
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.002	0.000	0.001	0.000	0.000	0.000	0.002
3	0.003	0.000	0.002	0.000	0.000	0.000	0.005
4	0.000	0.002	0.005	0.002	0.000	0.000	0.008
5	0.004	0.000	0.007	0.000	0.000	0.000	0.012
6	0.005	0.014	0.011	0.008	0.000	0.000	0.037
7	0.005	0.021	0.014	0.012	0.000	0.000	0.053
8	0.000	0.027	0.018	0.016	0.000	0.000	0.062
9	0.005	0.032	0.021	0.020	0.001	0.000	0.078
10	0.006	0.000	0.022	0.000	0.000	0.000	0.029
11	0.006	0.037	0.024	0.023	0.000	0.000	0.090
12	0.000	0.038	0.024	0.024	0.000	0.000	0.086
13	0.006	0.038	0.026	0.024	0.000	0.000	0.093
14	0.006	0.038	0.026	0.024	0.000	0.000	0.095

Table 23: Construction adaptation measures against storms

Year after Start	Red River Delta	Northern midland and mountain area	Northern Central area and Central coastal area	Central Highlands	South East	Mekong River Delta	Vietnam
Benefit (avoided Damage)							
15	0.006	0.000	0.026	0.000	0.000	0.000	0.033
16	0.000	0.041	0.027	0.025	0.000	0.000	0.093
17	0.006	0.043	0.027	0.025	0.000	0.001	0.102
18	0.006	0.044	0.028	0.026	0.000	0.000	0.104
19	0.006	0.044	0.029	0.026	0.000	0.001	0.106
20	0.000	0.000	0.030	0.000	0.000	0.001	0.030
21	0.006	0.045	0.030	0.027	0.000	0.000	0.108
22	0.006	0.046	0.030	0.027	0.000	0.001	0.109
23	0.006	0.046	0.030	0.027	0.000	0.001	0.109
24	0.000	0.046	0.030	0.027	0.000	0.000	0.103
25	0.006	0.000	0.030	0.000	0.000	0.001	0.037
26	0.006	0.046	0.030	0.027	0.000	0.001	0.110
27	0.006	0.046	0.030	0.027	0.000	0.000	0.109
28	0.000	0.046	0.030	0.027	0.000	0.001	0.103
29	0.006	0.046	0.030	0.027	0.000	0.001	0.110
30	0.006	0.000	0.030	0.000	0.000	0.000	0.037
31	0.006	0.046	0.030	0.027	0.000	0.001	0.110
32	0.000	0.046	0.030	0.027	0.000	0.001	0.103
33	0.006	0.046	0.030	0.027	0.000	0.000	0.109
34	0.006	0.046	0.030	0.027	0.000	0.001	0.110
35	0.006	0.000	0.030	0.000	0.000	0.001	0.037
36	0.000	0.046	0.030	0.027	0.000	0.000	0.103
37	0.006	0.046	0.030	0.027	0.000	0.001	0.110
38	0.006	0.046	0.030	0.027	0.000	0.001	0.110
39	0.006	0.046	0.030	0.027	0.000	0.000	0.109
40	0.000	0.000	0.030	0.000	0.000	0.001	0.031
Cost (to avoid Damage)							
1	0.003	0.000	0.001	0.000	0.000	0.000	0.004
2	0.013	0.000	0.007	0.000	0.000	0.000	0.020
3	0.013	0.002	0.015	0.000	0.000	0.000	0.030
4	0.010	0.016	0.023	0.019	0.000	0.000	0.067
5	0.004	0.051	0.029	0.027	0.000	0.000	0.111
6	0.005	0.066	0.034	0.033	0.000	0.000	0.137
7	0.002	0.078	0.034	0.044	0.000	0.005	0.163
8	0.002	0.059	0.040	0.038	0.000	0.000	0.139
9	0.001	0.044	0.026	0.037	0.000	0.000	0.108
10	0.004	0.023	0.018	0.025	0.000	0.000	0.069
11	0.001	0.031	0.016	0.003	0.000	0.000	0.050
12	0.002	0.008	0.005	0.010	0.000	0.000	0.024
13	0.002	0.003	0.011	0.001	0.000	0.000	0.016
14	0.001	0.004	0.004	0.006	0.000	0.000	0.016
15	0.000	0.014	0.005	0.003	0.000	0.000	0.022
16	0.000	0.016	0.005	0.004	0.000	0.000	0.025
17	0.000	0.016	0.007	0.005	0.000	0.001	0.029
18	0.000	0.012	0.006	0.005	0.000	0.000	0.024
19	0.000	0.008	0.005	0.004	0.000	0.000	0.017
20	0.000	0.005	0.011	0.002	0.000	0.000	0.019
21	0.000	0.006	0.004	0.001	0.000	0.000	0.011
22	0.000	0.002	0.001	0.001	0.000	0.000	0.004
23	0.000	0.001	0.002	0.001	0.000	0.000	0.004
24	0.000	0.000	0.000	0.000	0.000	0.000	0.001
25	0.000	0.002	0.000	0.000	0.000	0.000	0.003
26	0.000	0.000	0.000	0.000	0.000	0.000	0.001
27	0.000	0.000	0.000	0.000	0.000	0.000	0.001
28	0.000	0.000	0.000	0.000	0.000	0.000	0.001
29	0.000	0.000	0.000	0.000	0.000	0.000	0.001
30	0.000	0.000	0.001	0.000	0.000	0.000	0.001
31	0.000	0.000	0.000	0.000	0.000	0.000	0.001
32	0.000	0.000	0.000	0.000	0.000	0.000	0.001
33	0.000	0.000	0.000	0.000	0.000	0.000	0.001
34	0.000	0.000	0.000	0.000	0.000	0.000	0.001
35	0.000	0.000	0.000	0.000	0.000	0.000	0.001
36	0.000	0.000	0.000	0.000	0.000	0.000	0.001
37	0.000	0.000	0.000	0.000	0.000	0.000	0.001
38	0.000	0.000	0.000	0.000	0.000	0.000	0.001

Table 23: Construction adaptation measures against storms

Year after Start	Red River Delta	Northern midland and mountain area	Northern Central area and Central coastal area	Central Highlands	South East	Mekong River Delta	Vietnam
Benefit (avoided Damage)							
39	0.000	0.000	0.000	0.000	0.000	0.000	0.001
40	0.000	0.000	0.000	0.000	0.000	0.000	0.001

Source: Nam, Long, Sam, Hai & Hai (2021) and own computation.

Table 24: Damages caused by sea-level rise

SLR	Red River Delta	Northern midland and mountain area	Northern Central area and Central coastal area	Central Highlands	South East	Mekong River Delta
Damages						
0	0.001	0.000	0.002	0.000	0.001	0.002
5	0.001	0.000	0.004	0.000	0.003	0.004
10	0.001	0.000	0.008	0.000	0.006	0.009
15	0.002	0.000	0.010	0.000	0.010	0.014
20	0.002	0.000	0.013	0.000	0.017	0.023
25	0.003	0.000	0.016	0.000	0.018	0.025
30	0.004	0.000	0.020	0.000	0.020	0.029
35	0.004	0.000	0.023	0.000	0.021	0.031
40	0.005	0.000	0.027	0.000	0.023	0.035
45	0.006	0.000	0.032	0.000	0.024	0.040
50	0.007	0.000	0.036	0.000	0.027	0.044
55	0.008	0.000	0.039	0.000	0.029	0.048
60	0.009	0.000	0.044	0.000	0.032	0.053
65	0.011	0.000	0.048	0.000	0.034	0.058
70	0.012	0.000	0.052	0.000	0.037	0.063
75	0.014	0.000	0.056	0.000	0.040	0.068
80	0.015	0.000	0.062	0.000	0.043	0.074
85	0.017	0.000	0.067	0.000	0.045	0.080
90	0.019	0.000	0.071	0.000	0.048	0.086
95	0.021	0.000	0.083	0.000	0.052	0.095
Benefits						
0	0.001	0.000	0.004	0.000	0.002	0.003
5	0.001	0.000	0.003	0.000	0.003	0.004
10	0.001	0.000	0.008	0.000	0.006	0.008
15	0.001	0.000	0.004	0.000	0.008	0.011
20	0.001	0.000	0.005	0.000	0.014	0.019
25	0.001	0.000	0.006	0.000	0.002	0.003
30	0.001	0.000	0.008	0.000	0.003	0.004
35	0.001	0.000	0.006	0.000	0.002	0.003
40	0.001	0.000	0.007	0.000	0.004	0.005
45	0.002	0.000	0.010	0.000	0.003	0.005
50	0.002	0.000	0.007	0.000	0.005	0.007
55	0.002	0.000	0.007	0.000	0.004	0.006
60	0.003	0.000	0.008	0.000	0.005	0.007
65	0.003	0.000	0.009	0.000	0.004	0.006
70	0.003	0.000	0.007	0.000	0.006	0.008
75	0.003	0.000	0.008	0.000	0.005	0.007
80	0.004	0.000	0.012	0.000	0.006	0.008
85	0.004	0.000	0.009	0.000	0.005	0.007
90	0.004	0.000	0.009	0.000	0.006	0.008
95	0.004	0.000	0.021	0.000	0.008	0.011

Source: Nam et al. (2020) and own computation.

Table 25: Upscaling assumptions drainage

Assumption	Value
general	
share of urban area flooded to impacted area	13.45%
share of impacted area to total area of a province	80%
effectiveness of adaptation measure to reduce flooded area	80%
floods per rainy day	70%
average housing area	82.2m^2
cost norm to build a new house (million VND per m^2)	7.33
investment rate infrastructure in urban area (billion VND per km^2)	814
annual maintenance and operation cost	
flooded house (billion VND per km^2)	0.37
non-flooded house (billion VND per km^2)	0.14
flooded infrastructure (billion VND per km^2)	48.84
non-flooded infrastructure (billion VND per km^2)	29.80
project implementation cost	
capital expenditure cost (billion VND per km^2)	177.79
annual maintenance and operation (billion VND per km^2)	2.70

Source: Thanh et al. (2020) and own computation.

Table 26: Land loss due to sea-level rise $ll_{b,s,r}$

SL_b in cm	Services			
	Red River Delta	North Central and Central Coastal Area	South East	Mekong River Delta
0	0.0543	0.0054	0.0002	0.0466
5	0.2125	0.0169	0.0070	0.1048
10	0.2569	0.0207	0.0105	0.1591
15	0.4734	0.0306	0.0137	0.3276
20	0.7051	0.0374	0.0175	0.4450
25	0.9533	0.0460	0.0247	0.6959
30	1.0982	0.0538	0.0307	0.7132
35	1.2360	0.0648	0.0370	0.7417
40	1.3821	0.0751	0.0447	0.8200
45	1.5189	0.0848	0.0514	0.8326
50	1.7373	0.0937	0.0613	0.8993
55	2.0696	0.1062	0.0730	1.1480
60	2.0696	0.1062	0.0730	1.1480
65	2.0696	0.1062	0.0730	1.1480
70	2.2687	0.1133	0.0802	1.2319
75	2.4615	0.1197	0.0878	1.3493
80	2.6638	0.1261	0.0971	1.4374
85	2.8729	0.1357	0.1075	1.5454
90	3.1044	0.1461	0.1185	1.6273
95	3.3344	0.1850	0.2690	1.6670
SLR	Water			
	Red River Delta	North Central and Central Coastal Area	South East	Mekong River Delta
0	0.0020	0.0022	0.0000	0.0011
5	0.0033	0.0029	0.0006	0.0037
10	0.0041	0.0035	0.0031	0.0062
15	0.0073	0.0046	0.0042	0.0105
20	0.0087	0.0050	0.0050	0.0132
25	0.0099	0.0057	0.0060	0.0197
30	0.0118	0.0063	0.0066	0.0213
35	0.0129	0.0070	0.0073	0.0226
40	0.0146	0.0077	0.0081	0.0241
45	0.0159	0.0081	0.0088	0.0254
50	0.0171	0.0086	0.0094	0.0282
55	0.0192	0.0097	0.0104	0.0338
60	0.0192	0.0097	0.0104	0.0338
65	0.0192	0.0097	0.0104	0.0338
70	0.0205	0.0102	0.0109	0.0375
75	0.0218	0.0106	0.0118	0.0410
80	0.0230	0.0111	0.0125	0.0442
85	0.0242	0.0118	0.0134	0.0478
90	0.0258	0.0123	0.0143	0.0512
95	0.0270	0.0138	0.0323	0.0535
SLR	Energy			
	Red River Delta	Central Region	Southern region	Mekong River Delta
0	0.0001	0.0000	0.0000	0.0002
5	0.0003	0.0000	0.0000	0.0005
10	0.0003	0.0000	0.0000	0.0006
15	0.0003	0.0000	0.0000	0.0008
20	0.0004	0.0000	0.0000	0.0010
25	0.0005	0.0000	0.0000	0.0013
30	0.0006	0.0000	0.0000	0.0014
35	0.0007	0.0000	0.0000	0.0015
40	0.0008	0.0000	0.0000	0.0017
45	0.0009	0.0000	0.0000	0.0018
50	0.0010	0.0000	0.0000	0.0018
55	0.0012	0.0000	0.0000	0.0023
60	0.0012	0.0000	0.0000	0.0023
65	0.0012	0.0000	0.0000	0.0023
70	0.0013	0.0000	0.0000	0.0026
75	0.0014	0.0000	0.0000	0.0028
80	0.0015	0.0000	0.0000	0.0028
85	0.0016	0.0000	0.0000	0.0029
90	0.0017	0.0001	0.0001	0.0030
95	0.0018	0.0001	0.0001	0.0031
SLR	Manufacturing			

	Red River Delta	North Central and Central Coastal Area	South East	Mekong River Delta
0	0.0208	0.0028	0.0000	0.0068
5	0.0396	0.0090	0.0097	0.0158
10	0.0493	0.0105	0.0228	0.0268
15	0.0667	0.0126	0.0339	0.0515
20	0.0886	0.0134	0.0450	0.0950
25	0.1170	0.0145	0.0553	0.2037
30	0.1409	0.0153	0.0649	0.2072
35	0.1605	0.0257	0.0749	0.2110
40	0.1813	0.0330	0.0847	0.2169
45	0.1977	0.0355	0.0944	0.2201
50	0.2198	0.0376	0.1154	0.2401
55	0.2530	0.0410	0.1352	0.2611
60	0.2530	0.0410	0.1352	0.2611
65	0.2530	0.0410	0.1352	0.2611
70	0.2709	0.0448	0.1456	0.2804
75	0.2879	0.0470	0.1573	0.3008
80	0.3065	0.0494	0.1708	0.3174
85	0.3298	0.0530	0.1877	0.3339
90	0.3527	0.0575	0.2075	0.3519
95	0.3787	0.0748	0.4680	0.3723
SLR		Health		
	Red River Delta	North Central and Central Coastal Area	South East	Mekong River Delta
0	0.0000	0.0000	0.0000	0.0010
5	0.0012	0.0000	0.0001	0.0016
10	0.0014	0.0000	0.0001	0.0022
15	0.0015	0.0000	0.0001	0.0030
20	0.0022	0.0001	0.0001	0.0051
25	0.0024	0.0001	0.0001	0.0073
30	0.0037	0.0001	0.0002	0.0074
35	0.0046	0.0001	0.0002	0.0079
40	0.0055	0.0001	0.0003	0.0088
45	0.0063	0.0001	0.0003	0.0095
50	0.0068	0.0002	0.0005	0.0106
55	0.0103	0.0003	0.0005	0.0137
60	0.0103	0.0003	0.0005	0.0137
65	0.0103	0.0003	0.0005	0.0137
70	0.0111	0.0004	0.0006	0.0146
75	0.0123	0.0005	0.0007	0.0158
80	0.0129	0.0005	0.0008	0.0170
85	0.0136	0.0006	0.0008	0.0187
90	0.0142	0.0006	0.0010	0.0197
95	0.0148	0.0007	0.0045	0.0204

Source: Nam, Long, Sam & Tuan (2021) and own computation.

Table 27: Dyke adaptation costs $G^{dyke}_{s,r,t}$ (million VND)

Year	Red River Delta	Northern midland and mountain area	Northern coastal and coastal area	Central Highlands	South East	Mekong River
2021	859173.0194	0	33342.4721	0	1481.504193	55414.67283
2022	1773291.931	0	33342.4721	0	1481.504193	55414.67283
2023	2419853.91	0	33342.4721	0	1481.504193	55414.67283
2024	383083.7043	0	42972.26669	0	1481.504193	55414.67283
2025	335580.6198	0	33801.03374	0	1481.504193	55414.67283
2026	267617.3951	0	33801.03374	0	1481.504193	55414.67283
2027	255637.3933	0	33801.03374	0	1481.504193	55414.67283
2028	654945.0833	0	33801.03374	0	1481.504193	55414.67283
2029	266981.0446	0	33801.03374	0	1481.504193	55414.67283
2030	266981.0446	0	33801.03374	0	1481.504193	55414.67283
2031	280047.7625	0	33801.03374	0	1481.504193	55414.67283
2032	267603.2693	0	33801.03374	0	1481.504193	55414.67283
2033	267603.2693	0	33801.03374	0	1481.504193	55414.67283
2034	267603.2693	0	33801.03374	0	1481.504193	55414.67283
2035	267603.2693	0	33801.03374	0	1481.504193	55414.67283
2036	323373.1284	0	33801.03374	0	1481.504193	55414.67283
2037	270258.9768	0	33801.03374	0	1481.504193	55414.67283
2038	270258.9768	0	33801.03374	0	1481.504193	55414.67283
2039	270258.9768	0	33801.03374	0	1481.504193	55414.67283
2040	270258.9768	0	33801.03374	0	1481.504193	55414.67283
2041	727768.0303	0	33801.03374	0	1481.504193	55414.67283
2042	292045.1222	0	33801.03374	0	1481.504193	55414.67283
2043	292045.1222	0	33801.03374	0	1481.504193	55414.67283
2044	292045.1222	0	33801.03374	0	1481.504193	55414.67283
2045	292045.1222	0	33801.03374	0	1481.504193	55414.67283
2046	292045.1222	0	33801.03374	0	1481.504193	55414.67283
2047	292045.1222	0	33801.03374	0	1481.504193	55414.67283
2048	292045.1222	0	33801.03374	0	1481.504193	55414.67283
2049	292045.1222	0	33801.03374	0	1481.504193	55414.67283
2050	292045.1222	0	33801.03374	0	1481.504193	55414.67283

SourceNam, Long, Sam & Tuan (2021) and own computation.

C Model equations for DGE-CRED

C.1 Equations for the aggregate sector

aggregate sectoral production

$$P^{A}_{k\ t}\, Q^{A}_{k\ t} = \sum_{s}^{S} P^{D}_{s\ t}\, Q^{D}_{s\ t} \tag{82}$$

demand for aggregate sectoral products

$$\frac{P^{A}_{k\ t}}{P^{D}_{\ t}} = \omega_k^{Q^A\ \frac{1}{\eta^Q}} \left(\frac{Q^{A}_{k\ t}}{Q^{D}_{\ t}}\right)^{\frac{(-1)}{\eta^Q}} \tag{83}$$

Households FOC for capital stock

$$\left(\mathbb{E}_t P_{t+1}\right) \left(\mathbb{E}_t r_{k,r,t+1}\right) \left(\mathbb{E}_t \lambda_{t+1}\right) \beta \left(1 - \left(\mathbb{E}_t \tau^{K^H}_{t+1}\right)\right) + (1-\delta)\, \beta \left(\mathbb{E}_t \lambda_{t+1}\right) \left(\mathbb{E}_t \omega^{I}_{k,r,t+1}\right) = \lambda_t\, \omega^{I}_{s,r,t} \tag{84}$$

Households FOC for investment into capital stock

$$\begin{aligned}
&P_t\, \lambda_t \\
&= \lambda_t\, \omega^{I}_{s,r,t} \left(1 - \left(\exp\left(\sqrt{\frac{\phi^K}{2}} \left(\frac{\frac{I_{k,r_t}}{I_{k,r_{t-1}}}\, PoP_{t-1}}{PoP_t} - 1\right)\right) + \exp\left(\left(\frac{\frac{I_{k,r_t}}{I_{k,r_{t-1}}}\, PoP_{t-1}}{PoP_t} - 1\right) \left(-\sqrt{\frac{\phi^K}{2}}\right)\right) - 2\right)\right. \\
&\quad \left. - \sqrt{\frac{\phi^K}{2}}\, \frac{\frac{I_{k,r_t}}{I_{k,r_{t-1}}}\, PoP_{t-1}}{PoP_t} \left(\exp\left(\sqrt{\frac{\phi^K}{2}} \left(\frac{I_{k,r_t}}{I_{k,r_{t-1}}} - 1\right)\right) - \exp\left(\left(\frac{\frac{I_{k,r_t}}{I_{k,r_{t-1}}}\, PoP_{t-1}}{PoP_t} - 1\right) \left(-\sqrt{\frac{\phi^K}{2}}\right)\right)\right)\right) \\
&\quad + \sqrt{\frac{\phi^K}{2}}\, \frac{\left(\mathbb{E}_t \omega^{I}_{k,r,t+1}\right) \frac{\beta \left(\frac{\mathbb{E}_t C_{t+1}}{\mathbb{E}_t PoP_{t+1}}\right)^{(-\sigma^C)}}{\left(\mathbb{E}_t P_{t+1}\right)\left(1 + \mathbb{E}_t \tau^{C}_{t+1}\right)} \left(\mathbb{E}_t I_{k,r,t+1}\right)^2}{I_{k,r_t}^{\ 2}} \left(\frac{PoP_t}{\mathbb{E}_t PoP_{t+1}}\right)^2 \left(\exp\left(\sqrt{\frac{\phi^K}{2}} \left(\frac{PoP_t\, \frac{\mathbb{E}_t I_{k,r,t+1}}{I_{k,r_t}}}{\mathbb{E}_t PoP_{t+1}} - 1\right)\right)\right. \\
&\quad \left. - \exp\left(\left(-\sqrt{\frac{\phi^K}{2}}\right) \left(\frac{PoP_t\, \frac{\mathbb{E}_t I_{k,r,t+1}}{I_{k,r_t}}}{\mathbb{E}_t PoP_{t+1}} - 1\right)\right)\right)
\end{aligned} \tag{85}$$

Law of motion for capital stock used in aggregate sector

$$\begin{aligned}
\frac{K_{k,r_t}}{PoP_t} &= \frac{(1-\delta)\, K_{k,r_{t-1}}}{PoP_{t-1}} \\
&\quad + \left(1 - \left(\exp\left(\sqrt{\frac{\phi^K}{2}} \left(\frac{\frac{I_{k,r_t}}{I_{k,r_{t-1}}}\, PoP_{t-1}}{PoP_t} - 1\right)\right) + \exp\left(\left(\frac{\frac{I_{k,r_t}}{I_{k,r_{t-1}}}\, PoP_{t-1}}{PoP_t} - 1\right) \left(-\sqrt{\frac{\phi^K}{2}}\right)\right) - 2\right)\right) \frac{I_{k,r_t}}{PoP_t} \\
&\quad - \frac{D_{s,r,t}}{PoP_t}
\end{aligned} \tag{86}$$

aggregate capital stock

$$P_t\, K_{k,r_{t-1}} = \sum_{s}^{S} P_{s,r,t}\, K_{s,r,t} \tag{87}$$

aggregate investment into the capital stock

$$I_{k\,t} = \sum_{r}^{R} I_{k,r,t} \tag{88}$$

C.2 Equations for the regional subsector

sector specific corporate tax rate paid by firms

$$\tau^{K}_{s,r,t} = \tau^{K,F}_{s,r} + \eta_{\tau^K,s,r_t} \tag{89}$$

sector specific labour tax rate paid by firms

$$\tau^{N}_{s,r,t} = \tau^{N,F}_{s,r} + \eta_{\tau^N,s,r_t} \tag{90}$$

sector and capital specific productivity shock

$$A_{s,r,t} = A_{s,r}\, {K^{G}_{t}}^{\phi^G} \exp\left(\eta_{A,s,r_t}\right) \tag{91}$$

sector and capital specific productivity shock

$$A^{K}_{s,r,t} = \exp\left(\eta_{A^K,s,r_t}\right) \tag{92}$$

sector and labour specific productivity shock

$$A^N_{s,r,t} = \exp\left(\eta_{A^N,s,r_t}\right) \tag{93}$$

sector specific damage function

$$D_{s,r,t} = \eta_{D,s,r_t} \tag{94}$$

sector specific damage function on labour productivity

$$D^N_{s,r,t} = \eta_{D^N,s,r_t} \tag{95}$$

sector specific damage function on capital formation

$$D^K_{s,r,t} = \eta_{D^K,s,r_t}\, Y_0 \tag{96}$$

sector specific private adaptation expenditures against climate change

$$K^{A,P}_{s,r\ \ t} = \frac{Y_0\, \eta_{I^{A,P},s,r_t}}{P_t\, \prod_{m=1}^{S} P^{D\,1(i^{A,P}_s=m)}_m} \tag{97}$$

sector specific private adaptation capital against climate change

$$K^{A,P}_{s,r\ \ t} = I^{A,P}_{s,r\ \ t} + \left(1 - \delta^{K^A_{k,r}}\right)\, K^{A,P}_{s,r\ \ t-1} \tag{98}$$

sector specific adaptation expenditures by the government against climate change

$$K^A_{s,r_t} = \frac{Y_0\, \eta_{G^A,s,r_t}}{P_t\, \prod_{m=1}^{S} P^{D\,1(i^{G^A}_s=m)}_m} \tag{99}$$

sector specific adaptation capital against climate change

$$K^A_{s,r_t} = G^A_{s,r_t} + \left(1 - \delta^{K^A_{k,r}}\right)\, K^A_{s,r_{t-1}} \tag{100}$$

demand for regional sector output

$$P_{s,r_t} = P^D_{s\ \ t}\, {\omega^Q_{k,r}}^{\frac{1}{\eta^Q_k}} \left(\frac{Q_{s,r_t}}{Q_{s_t}}\right)^{\frac{(-1)}{\eta^Q_k}} \tag{101}$$

demand for regional sector value added

$$P_{s,r_t} = P^D_{s,r_t} \left(1 - \omega^{Q^I}_{k,r}\right)^{\frac{1}{\eta^I_k}} \left(\frac{Y_{s,r_t}}{Q_{s,r_t}}\right)^{\frac{(-1)}{\eta^I_k}} \tag{102}$$

regional sector demand for intermediates

$$P_t = P^D_{s,r_t}\, {\omega^{Q^I}_{k,r}}^{\frac{1}{\eta^I_k}} \left(\frac{Q^I_{s,r_t}}{Q_{s,r_t}}\right)^{\frac{(-1)}{\eta^I_k}} \tag{103}$$

sector specific gross value added

$$Y_{s,r,t} = A_{s,r,t}\, \left(1 - D_{s,r,t}\right) \begin{cases} \left(K_{s,r,t}\, A^K_{s,r,t}\right)^{\alpha^K_{s,r}} \left(A^N_{s,r,t}\, PoP_t\, \left(1 - D_{s,r,t}\right)\, N_{s,r,t}\right)^{\alpha^N_{s,r}} & \eta^{N,K}_{s,r} = 1 \\ \left({\alpha^K_{s,r}}^{\frac{1}{\eta^{N,K}_{s,r}}} \left(K_{s,r,t}\, A^K_{s,r,t}\right)^{\rho^{N,K}_{s,r}} + {\alpha^N_{s,r}}^{\frac{1}{\eta^{N,K}_{s,r}}} \left(A^N_{s,r,t}\, PoP_t\, \left(1 - D_{s,r,t}\right)\, N_{s,r,t}\right)^{\rho^{N,K}_{s,r}}\right)^{\frac{1}{\rho^{N,K}_{s,r}}} & \eta^{N,K}_{s,r} \neq 1 \end{cases} \tag{104}$$

Firms FOC capital

$$r_{k,r_t}\, \left(1 + \tau^K_{s,r_t}\right) = {\alpha^K_{k,r}}^{\frac{1}{\eta^{N,K}_{k,r}}} \left(A^K_{s,r_t}\, A_{s,r_t}\, \left(1 - D_{s,r_t}\right)\right)^{\frac{\eta^{N,K}_{k,r}-1}{\eta^{N,K}_{k,r}}} \left(\frac{K_{s,r_t}}{Y_{s,r_t}}\right)^{\frac{(-1)}{\eta^{N,K}_{k,r}}} \tag{105}$$

Firms FOC labour ($PoP_t\, N_{s,r,t}$)

$$\frac{W_{s,r,t}\, \left(1 + \tau^N_{s,r,t}\right)}{P_{s,r,t}} = {\alpha^N_{s,r}}^{\frac{1}{\eta^{N,K}_{s,r}}} \left(A_{s,r,t}\, \left(1 - D_{s,r,t}\right)\, A^N_{s,r,t}\, \left(1 - D_{s,r,t}\right)\right)^{\frac{\eta^{N,K}_{s,r}-1}{\eta^{N,K}_{s,r}}} \left(\frac{PoP_t\, N_{s,r,t}}{Y_{s,r,t}}\right)^{\frac{(-1)}{\eta^{N,K}_{s,r}}} \tag{106}$$

Households FOC labour ($N_{s,r,t}$)

$$\lambda_t\, W_{s,r,t}\, \left(1 - {\tau^{N,H}}_t\right) = A^N_{s,r,t}\, \phi^L_{s,r}\, {N_{s,r,t}}^{\sigma^L} \tag{107}$$

output production function

$$Q_{s,r,t} = \left({\omega^{Q^I}_{s,r}}^{\frac{1}{\eta^I_s}}\, {Q^I_{s,r,t}}^{\frac{\eta^I_s-1}{\eta^I_s}} + \left(1 - \omega^{Q^I}_{s,r}\right)^{\frac{1}{\eta^I_s}}\, {Y_{s,r,t}}^{\frac{\eta^I_s-1}{\eta^I_s}}\right)^{\frac{\eta^I_s}{\eta^I_s-1}} \tag{108}$$

demand for subsectoral imports

$$\frac{P^M_{s\ t}}{P^M{}_t} = \omega^M_k{}^{\frac{1}{\eta^M}} \left(\frac{M_{st}}{M_t}\right)^{\frac{(-1)}{\eta^M}} \tag{109}$$

use of total subsectoral production

$$\begin{aligned} Q_{s,t} =& Q^D_{s\ t} + X_{st} + P_t\, G^{A,D^H}_t\, 1(i^{G^{A,H}} = s) + P_t\, I^{A,D^H}_t\, 1(i^{A,P,H} = s) \\ &+ \sum_{m=1}^{S} \sum_{r=1}^{R} \Big(P_t\, G^A_{m,r,t}\, 1(i^{G^A}_m = s) + P_t\, I^{A,P}_{m,r,t}\, 1(i^{A,P}_m = s)\Big) \end{aligned} \tag{110}$$

aggregate subsectoral production

$$P^D_{s,t}\, Q_{s\,t} = \sum_r^R P_{s,r,t}\, Q_{s,r,t} \tag{111}$$

aggregate subsectoral demand for intermediate inputs

$$P_t\, Q^I_{s,t} = P_t\, \sum_r^R Q^I_{s,r,t} \tag{112}$$

demand for subsectoral production

$$\frac{P^D_{s,t}}{P^A_{k,t}} = \omega^Q_k{}^{\frac{1}{\eta^{Q^A}_k}} \left(\frac{Q^D_{s,t}}{Q^A_{k,t}}\right)^{\frac{-1}{\eta^{Q^A}_k}} \tag{113}$$

aggregate subsectoral gross value added

$$Y_{s\,t} = \sum_r^R P_{s,r,t}\, Y_{s,r,t} \tag{114}$$

aggregate subsectoral labour

$$N_{s\,t} = \sum_r^R N_{s,r,t} \tag{115}$$

aggregate labour income in subsector

$$N_{s\,t}\, W_{s\,t} = \sum_r^R N_{s,r,t}\, W_{s,r,t} \tag{116}$$

subsectoral rented capital stock

$$P_t\, K_{s\,t} = \sum_r^R P_{s,r,t}\, K_{s,r,t} \tag{117}$$

subsectoral exports

$$X_{s,t} = D^X_s \left(\frac{P^D_{s,t}}{P^M_{s,t}}\right)^{-\eta^X} \tag{118}$$

share of products exported

$$D^X_{s\ t} = \frac{X_{s,t}}{Q_{s,t}} \tag{119}$$

total domestic output

$$P^D{}_t\, Q_t = \sum_s^S P^D_{s\ t}\, Q_{s\,t} \tag{120}$$

total domestic output used domestically

$$P^D{}_t\, Q^D{}_t = \sum_k^{S^A} P^A_{k\ t}\, Q^A_{k\ t} \tag{121}$$

total output used

$$P_t\, Q^U{}_t = P^D{}_t\, Q^D{}_t + P^M{}_t\, M_t \tag{122}$$

total gross value added

$$P_t\, Y_t = \sum_s^S \sum_r^R P_{s,r,t}\, Y_{s,r,t} \tag{123}$$

total intermediate output used

$$P_t\, Q^I{}_t = \sum_s^S P_t\, Q^I_{s\,t} \tag{124}$$

total investment

$$P_t\, I_t = \sum_k^{S^A} P_t\, I_{k\,t} \tag{125}$$

total exports

$$P^D{}_t\, X_t = \sum_s^S P^D_s{}_t\, X_{s\,t} \tag{126}$$

aggregate imports

$$P^M_t\, M_t = \sum_s^S P^M_{s,t}\, M_{s,t} \tag{127}$$

aggregate capital stock

$$P_t\, K_t = \sum_s^S P_t\, K_{s,t} \tag{128}$$

share of total hours worked on total time endowment

$$N_t = \sum_s^S N_{s,t} \tag{129}$$

demand for imported goods

$$\frac{P^M{}_t}{P_t} = \omega^F{}^{\frac{1}{\eta^F}} \left(\frac{M_t}{Q^U{}_t}\right)^{\frac{(-1)}{\eta^F}} \tag{130}$$

demand for domestic goods used domestically

$$\frac{P^D{}_t}{P_t} = \left(1-\omega^F\right)^{\frac{1}{\eta^F}} \left(\frac{Q^D{}_t}{Q^U{}_t}\right)^{\frac{-1}{\eta^F}} \tag{131}$$

resource constraint

$$\begin{aligned} Q_t\, \frac{P^D{}_t}{P_t} = {} & Q^I{}_t + NX_t + I_t + C_t + \frac{P^H{}_t}{P_t}\, I^H{}_t + G_t + G^{A,D^H}{}_t \prod_m^S P^D_{m,t}{}^{1(i^{G^{A,H}}=m)} + I^{A,P,H}{}_t \prod_m^S P^D_{m,t}{}^{1(i^{A,P,H}=m)} \\ & + + \sum_s^S \sum_r^R G^A_{s,r,t} \prod_m^S P^D_{m,t}{}^{1(i^{G^A}_s=m)} + \sum_{r=1}^R \sum_{s=1}^S I^{A,P}_{s,r,t} \prod_m^S P^D_{m,t}{}^{1(i^{A,P}_s=m)} \end{aligned} \tag{132}$$

aggregate price level

$$P_t = P_0\, \exp\left(\eta_{P\,t}\right) \tag{133}$$

import price

$$P^M{}_t = P^M_0 + \eta_{M\,t} \tag{134}$$

net exports

$$P_t\, NX_t = P^D{}_t\, X_t - P^M{}_t\, M_t \tag{135}$$

exogenous world interest rate

$$r^f{}_t = r^f_0 + \eta_{r^f\,t} \tag{136}$$

FOC households consumption

$$P_t\, \lambda_t\, \left(1+\tau^C{}_t\right) = (1-\gamma)\, \left(\frac{C_t}{PoP_t}\right)^{(-\gamma)} \left(\frac{H_t}{PoP_t}\right)^{\gamma} \left(\left(\frac{H_t}{PoP_t}\right)^{\gamma} \left(\frac{C_t}{PoP_t}\right)^{1-\gamma}\right)^{(-\sigma^C)} \tag{137}$$

law of motion for houses

$$\frac{H_t}{PoP_t} = \left(1-\delta^H\right)\, \frac{H_{t-1}}{PoP_{t-1}} + \frac{I^H{}_t}{PoP_t} - \frac{D^H{}_t}{PoP_t} \tag{138}$$

price for houses

$$P^H{}_t = P^H_0\, \exp\left(\eta_{H\,t}\right) \tag{139}$$

damages on housing induced by climate change

$$D^H{}_t = \frac{P_t\, Y_t\, \eta_{D^H\,t}}{P^H{}_t} \tag{140}$$

FOC households with respect to housing

$$\begin{aligned} \lambda_t\, \omega^H{}_t = \beta\, \Bigg(& \left(1-\delta^H\right)\, \left(\mathbb{E}_t\lambda_{t+1}\right)\, \left(\mathbb{E}_t\omega^H_{t+1}\right) \\ & + \gamma\, \left(\frac{\mathbb{E}_tC_{t+1}}{\mathbb{E}_tPoP_{t+1}}\right)^{1-\gamma} \left(\frac{H_t}{\mathbb{E}_tPoP_{t+1}}\right)^{\gamma-1} \left(\left(\frac{\mathbb{E}_tC_{t+1}}{\mathbb{E}_tPoP_{t+1}}\right)^{1-\gamma} \left(\frac{H_t}{\mathbb{E}_tPoP_{t+1}}\right)^{\gamma}\right)^{(-\sigma^C)} \Bigg) \end{aligned} \tag{141}$$

FOC households with respect to investment into housing

$$\lambda_t\, \omega^H{}_t = \lambda_t\, P^H{}_t\, \left(1+\tau^C{}_t\right) \tag{142}$$

FOC households with respect to foreign assets

$$\left(\mathbb{E}_t\lambda_{t+1}\right)\, \beta\, \left(1+\mathbb{E}_tr^f_{t+1}\right)\, \exp\left(\left(-\phi^B\right)\, \left(\frac{\mathbb{E}_tNX_{t+1}}{\mathbb{E}_tY_{t+1}} + \frac{\left(\mathbb{E}_tr^f_{t+1}\right)\, \left(\mathbb{E}_tB_{t+1}+BG_t\right)}{\mathbb{E}_tY_{t+1}}\right)\right) = \lambda_t \tag{143}$$

C.3 Government

taxes on labour income

$$\tau^{N,H}{}_t = \tau^{N,H} + \eta_{\tau^{N,H}}{}_t \tag{144}$$

taxes on capital income

$$\tau^{K,H}{}_t = \tau^{K,H} + \eta_{\tau^{K,H}}{}_t \tag{145}$$

taxes on consumption

$$\tau^C{}_t = \tau^C + \eta_{\tau^C}{}_t \tag{146}$$

taxes on housing

$$\tau^H{}_t = \tau^H + \eta_{\tau^C}{}_t \tag{147}$$

adaptation expenditures in housing

$$G^{A,D^H}{}_t = \frac{Y_0\, \eta_{G^{A,H}}{}_t}{P_t \prod_m^S P^D_{m,t}{}^{1(i^{G^{A,H}}=m)}} \tag{148}$$

government budget constraint

$$\begin{aligned}
&\sum_{r=1}^{R}\sum_{s=1}^{S} G^A_{s,r,t} \prod_m^S P^D_{m,t}{}^{1(i_s^{G^A}=m)} + G^{A,D^H}{}_t \prod_m^S P^D_{m,t}{}^{1(i^{G^{A,H}}=m)} + G_t + BG_t \\
&= K_{s,r,t}\, r_{k,r_t} \frac{P_{s,r,t}\left(\tau^{K,H}{}_t + \tau^K_{s,r,t}\right)}{P_t} + \frac{PoP_t\, N_{s,r,t}\, W_{s,r,t}\left(\tau^N_{s,r,t} + \tau^{N,H}{}_t\right)}{P_t} + I^H{}_t \frac{P^H{}_t\, \tau^C{}_t}{P_t} \\
&\quad + \tau^C{}_t\, C_t + \left(1 + r^f{}_t\right) BG_{t-1} \exp\left(\left(-\phi^B\right)\left(\frac{NX_t}{Y_t} + \frac{r^f{}_t\, (B_{t-1} + BG_{t-1})}{Y_t}\right)\right)
\end{aligned} \tag{149}$$

public capital stock

$$K^G{}_t = G_t + \left(1 - \delta^{K^G}\right) K^G{}_{t-1} \tag{150}$$

public foreign debt

$$BG_t = \eta_{BG\,t} \tag{151}$$

population

$$PoP_t = PoP_0 \exp\left(\eta_{PoP\,t}\right) \tag{152}$$

C.4 Climate variables

temperature

$$tas_{rt} = tas_{0,r} + \eta_{tas,r_t} \tag{153}$$

surface wind speed

$$SfcWind_{r,t} = SfcWind_{0,r} + \eta_{SfcWind,r,t} \tag{154}$$

precipitation

$$pr_{r,t} = pr_{0,r} + \eta_{pr,r,t} \tag{155}$$

sunshine influx

$$sunshine_{rt} = sunshine_{0,r} + \eta_{sunshine,r_t} \tag{156}$$

relative surface humidity

$$hurs_{rt} = hurs_{0,r} + \eta_{hurs,r_t} \tag{157}$$

heatwave

$$heatwave_{rt} = heatwave_{0,r} + \eta_{heatwave,r_t} \tag{158}$$

maximum consecutive dry days

$$maxdrydays_{r_t} = maxdrydays_{0,r} + \eta_{maxdrydays,r_t} \tag{159}$$

maximum consecutive wet days

$$maxwetdays_{r_t} = maxwetdays_{0,r} + \eta_{maxwetdays,r_t} \tag{160}$$

number of storms per year

$$storms_{rt} = storms_{0,r} + \eta_{storms,r_t} \tag{161}$$

number of floods per year

$$floods_{rt} = floods_{0,r} + \eta_{floods,r_t} \tag{162}$$

number of fires per year

$$fire_{rt} = fire_{0,r} + \eta_{fire,r_t} \tag{163}$$

number of land slides per year

$$landslide_{rt} = landslide_{0,r} + \eta_{landslide,r_t} \tag{164}$$

sea level

$$SL_t = SL_0 + \eta_{SL,r_t} \tag{165}$$

D Calibration of DGE-CRED model

```
function [fval_vec,strpar,strys] = Calibration(x,strys,strexo,strpar)
    % function [ys,check] = Calibration(strys,strexo,strpar)
    % calibrates the parameters of the DGE_CRED_Model.mod
    % Inputs:
    %      strys      [structure]  endogeonous variables of the model
    %      strexo     [structure]  exogeonous variables of the model
    %      strpar     [structure]  parameters of the model
    %
    % Output:
    %      fval_vec   [numeric]    difference between demand and supply
    %                              for imports for a given national
    %                              price level
    %      strys      [structure]  see inputs
    %      strpar     [structure]  see inputs


    % assign initial value for national price level
    strys.P = x;

    % update parameter value for initila price level
    strpar.P0_p = strys.P;

    %% calculate exogenous variables
    [strys,strpar, strexo] = AssignPredeterminedVariables(strys,strpar,strexo);


    % assign value for initial gross vlaue added
    strys.Y = strpar.Y0_p./strys.P;

    % compute foreign interest rate
    strys.rf = 1/strpar.beta_p 1;

    % compute foreeing interest rate
    strpar.rf0_p = 1/strpar.beta_p 1;

    % assign value for effective exchange rate
    strys.Sf = 0;

    % population
    strys.PoP = strpar.PoP0_p * exp(strexo.exo_PoP);

    % housing area
    strys.H = strpar.H0_p * strys.PoP;

    % hours worked as share of total available hours
    strys.N = strpar.N0_p;

    if strpar.iGAH_p == 0
        % adaptation measures in the housing sector
        strys.G_A_DH = strexo.exo_G_A_DH * strpar.Y0_p / strpar.P0_p;
    end

    if strpar.iIAPH_p == 0
        % private adaptation measures in the housing sector
        strys.I_AP_DH = strexo.exo_I_AP_DH * strpar.Y0_p / strpar.P0_p;
    end

    %% calculate sectoral and regional production factors and output

    for icosec = 1:strpar.inbsectors_p
        ssec = num2str(icosec);

        % sectoral interat rate
        strys.(['r_' ssec]) = (1/strpar.beta_p   1 ...
                                + strpar.delta_p)/(1   strys.tauKH);
        for icoreg = 1:strpar.inbregions_p
            sreg = num2str(icoreg);

            % subsectoral interat rate
            strys.(['r_' ssec '_' sreg]) = (1/strpar.beta_p   1 + strpar.delta_p)/(1   strys.tauKH);

            for icosubsec = strpar.(['substart_' ssec '_p']):strpar.(['subend_' ssec '_p'])
                ssubsec = num2str(icosubsec);

                % labour productivity
                strys.(['A_N_' ssubsec '_' sreg]) = strpar.(['A_N_' ssubsec '_' sreg '_p']);

                % sectoral productivity
                strys.(['A_' ssubsec '_' sreg]) = strpar.(['A_' ssubsec '_' sreg '_p']);
```

```
                % initial allocation of hours wotked
                strys.(['N_' ssubsec '_' sreg]) = strpar.(['phiN0_' ssubsec '_' sreg '_p']) * strys.N;
            end
        end
    end

    for icosec = 1:strpar.inbsectors_p
        ssec = num2str(icosec);
        % intitialize sectoral capital stock
        strys.(['KH_' ssec]) = 0;
            for icoreg = 1:strpar.inbregions_p
                sreg = num2str(icoreg);
                % intitialize sectoral and regional capital stock
                strys.(['KH_' ssec '_' sreg]) = 0;

                for icosubsec = strpar.(['substart_' ssec '_p']):strpar.(['subend_' ssec '_p'])
                    ssubsec = num2str(icosubsec);
                    stemp = [ssubsec '_' sreg];

                    % degree of substitutability beween capital and labour
                    rhotemp = ((strpar.(['etaNK_' ssubsec '_' sreg '_p']) 1)/strpar.(['etaNK_' stemp '_p']));

                    % interest rate including taxes
                    rkgross = strys.(['r_' ssec '_' sreg]) * (1 + strys.(['tauKF_' stemp]));

                    %Differentiate between Cobb Douglas or CES
                    if strpar.(['etaNK_' stemp '_p']) == 1
                        % subsectoral and regional real labour costs
                        wtemp = (((1 strys.(['D_' stemp])) * strys.(['A_' stemp])) / ...
                        (rkgross / ((1 strpar.(['phiW_' stemp '_p']))...
                        * strys.(['A_K_' stemp])))^(1 strpar.(['phiW_' stemp '_p'])))^(1/strpar.(['phiW_' stemp '_p'])) * ...
                        strys.(['A_N_' stemp]) * (1 strys.(['D_N_' stemp]));

                    else
                        % subsectoral and regional real labour costs
                        wtemp = ((((1 strys.(['D_' stemp])) * strys.(['A_' stemp]))^(1/strpar.(['etaNK_' stemp '_p']))...
                          (1 strpar.(['phiW_' stemp '_p'])) * (rkgross/strys.(['A_K_' stemp]))^(strpar.(['etaNK_' stemp '_p']) 1))...
                        / strpar.(['phiW_' stemp '_p']))^(1/(strpar.(['etaNK_' stemp '_p']) 1))...
                        * strys.(['A_N_' stemp]) * (1 strys.(['D_N_' stemp]));

                    end
                    % price level for gross value added
                    strys.(['P_' stemp]) = strpar.(['phiW_' stemp '_p'])/wtemp * strpar.(['phiY_' stemp '_p']) * strys.Y *strys.P /(strys.PoP * strys.(['N_' stemp]));

                    % distribtuion parameter for capital in production function
                    strpar.(['alphaK_' stemp '_p']) = (1 strpar.(['phiW_' stemp '_p'])) * (rkgross/ ((1 strys.(['D_' stemp])) * strys.(['A_' stemp]) * strys.(['A_K_' stemp]) * (1 strys.(['D_K_' stemp]))))^(strpar.(['etaNK_' stemp '_p']) 1);

                    % distribtuion parameter for labour in production function
                    strpar.(['alphaN_' stemp '_p']) = strpar.(['phiW_' stemp '_p']) * (wtemp/(((1 strys.(['D_N_' stemp])) * strys.(['A_N_' stemp]) * (1 strys.(['D_' stemp])) * strys.(['A_' stemp]))))^(strpar.(['etaNK_' stemp '_p']) 1);

                    % real gross value adde in the subsector and region
                    strys.(['Y_' stemp]) = strpar.(['phiY_' stemp '_p']) * strys.Y *strys.P / strys.(['P_' stemp]);

                    % capital stock used in the subsector and region
                    strys.(['K_' stemp]) = (1 strpar.(['phiW_' stemp '_p'])) * strys.(['Y_' stemp]) / rkgross;

                    % compute TFP
                    if strpar.(['etaNK_' stemp '_p']) == 1
                        strys.(['A_' stemp]) = strys.(['Y_' stemp]) / ((1 strys.(['D_' stemp])) * (strys.(['A_K_' stemp]) * strys.(['K_' stemp]))^strpar.(['alphaK_' stemp '_p']) * (strys.PoP * strys.(['A_N_' stemp]) * (1 strys.(['D_N_' stemp])) * strys.(['N_' stemp]))^strpar.(['alphaN_' stemp '_p']));
                    else
```

```
                    strys.(['A_' stemp]) = strys.(['Y_' stemp]) /((1  strys.(['D_' stemp])) * (strpar.(['alphaK_' stemp '_p'])^(1/strpar.(['etaNK_' stemp '_p'])) * (strys.(['A_K_' stemp]) * strys.(['K_' stemp]))^rhotemp + strpar.(['alphaN_' stemp '_p'])^(1/strpar.(['etaNK_' stemp '_p'])) * (strys.PoP * strys.(['A_N_' stemp]) * (1  strys.(['D_N_' stemp])) * strys.(['N_' stemp]))^rhotemp)^(1/rhotemp));
                end

                % compute capital stock in the sector and region
                strys.(['KH_' ssec '_' sreg]) = strys.(['KH_' ssec '_' sreg]) + strys.(['K_' stemp]) * strys.(['P_' stemp]) / strys.P;

                % wages in the subsector and region
                strys.(['W_' stemp]) = strpar.(['phiW_' stemp '_p']) * strys.(['Y_' stemp]) * strys.(['P_' stemp]) / (strys.PoP * strys.(['N_' stemp]) * (1 + strys.(['tauNF_' stemp])));

                % demand for intermediate propducts in the subsector and region
                strys.(['Q_I_' stemp]) = strys.(['Y_' stemp]) * strys.(['P_' stemp])  / strys.P * strpar.(['phiQI_' ssubsec '_p']) / (1  strpar.(['phiQI_' ssubsec '_p']));

                % auxiliary variable to compute distribution parameter
                tempQI = strys.P^strpar.(['etaI_' ssubsec '_p']) * strys.(['Q_I_' stemp]);

                % auxiliary variable to compute distribution parameter
                tempY = strys.(['P_' stemp])^strpar.(['etaI_' ssubsec '_p']) * strys.(['Y_' stemp]);

                % compute distribution parameter for production function for intermedate products
                strpar.(['omegaQI_' stemp '_p']) = tempQI / (tempY + tempQI);

                % compute price of products produced in the region and subsector
                strys.(['P_D_' stemp]) = (strpar.(['omegaQI_' stemp '_p']) * strys.P^(1 strpar.(['etaI_' ssubsec '_p'])) + (1  strpar.(['omegaQI_' stemp '_p']))...
                    * strys.(['P_' stemp])^(1  strpar.(['etaI_' ssubsec '_p'])))^(1/(1 strpar.(['etaI_' ssubsec '_p'])));

                % compute output in the region and subsector
                strys.(['Q_' stemp]) = (strys.(['P_' stemp]) * strys.(['Y_' stemp]) + strys.P * strys.(['Q_I_' stemp]))/strys.(['P_D_' stemp]);

            end

            % Lagrange multiplier for investment
            strys.(['omegaI_' ssec '_' sreg]) = strys.P;


            % compute sectoral and regional investment
            strys.(['I_' ssec '_' sreg]) = (strpar.delta_p) * strys.(['KH_' ssec '_' sreg]) + strys.(['D_K_' ssec '_' sreg]);

            % compute sectoral capital stock
            strys.(['KH_' ssec]) = strys.(['KH_' ssec]) + strys.(['KH_' ssec '_' sreg]);
        end
end

%% calculate sectoral and regional price indices and sectoral aggregates
for icosec = 1:strpar.inbsectors_p
    ssec = num2str(icosec);
    iasubsec = strpar.(['substart_' ssec '_p']):strpar.(['subend_' ssec '_p']);
    for icosubsec = iasubsec
        ssubsec = num2str(icosubsec);

        % initialize subsectoral aggregate of employment
        strys.(['N_' ssubsec]) = 0;

        % intitalize subsectoral price index
        strys.(['P_D_' ssubsec]) = 0;

        for icoreg = 1:strpar.inbregions_p
            sreg = num2str(icoreg);

            % compute distribution parameters across regions in one subsector sectors
            temp = 0;
            tempdenom = (strys.(['P_D_' ssubsec '_' sreg]) /((strys.(['Q_' ssubsec '_' sreg]))^(1/strpar.(['etaQ_' ssubsec '_p']))))^(strpar.(['etaQ_' ssubsec '_p']));
            for icoregm = 1:strpar.inbregions_p
                sregm = num2str(icoregm);
```

```
                    % compute numerator for distribution parameters across regions in one subsector
                    tempnum = (strys.(['P_D_' ssubsec '_' sregm]) / ((strys.(['Q_' ssubsec '_' sregm]))^(1/strpar.(['etaQ_' ssubsec '_p']))))^(strpar.(['etaQ_' ssubsec '_p']));


                    temp = temp + tempnum / tempdenom;
                end
                % distribution parameters across regions in one subsector sectors
                strpar.(['omegaQ_' ssubsec '_' sreg '_p']) = 1/temp;

                % aggregate labour across region in one sbsector
                strys.(['N_' ssubsec]) = strys.(['N_' ssubsec]) + strys.(['N_' ssubsec '_' sreg]);

                % aggregate price index across region in one sbsector
                strys.(['P_D_' ssubsec]) = strys.(['P_D_' ssubsec]) + strpar.(['omegaQ_' ssubsec '_' sreg '_p']) * strys.(['P_D_' ssubsec '_' sreg])^(1   strpar.(['etaQ_' ssubsec '_p']));
            end

            % aggregate price index across region in one sbsector
            strys.(['P_D_' ssubsec]) = strys.(['P_D_' ssubsec])^(1/(1   strpar.(['etaQ_' ssubsec '_p'])));

            % update intital aggregate price index across region in one sbsector
            strpar.(['P_D_' ssubsec '_p']) = strys.(['P_D_' ssubsec]);

            if strpar.iGAH_p == icosubsec
                % adaptation measures in the housing sector
                strys.G_A_DH = strexo.exo_G_A_DH * strpar.Y0_p / (strpar.P0_p * strpar.(['P_D_' ssubsec '_p']));
            end

            % inititlalize gross value added
            strys.(['Y_' ssubsec]) = 0;

            % inititlalize output
            strys.(['Q_' ssubsec]) = 0;

            % inititlalize gross vlaue added
            strys.(['Q_I_' ssubsec]) = 0;

            for icoreg = 1:strpar.inbregions_p
                sreg = num2str(icoreg);
                % aggregate gross value added
                strys.(['Y_' ssubsec]) = strys.(['Y_' ssubsec]) + strys.(['P_' ssubsec '_' sreg]) * strys.(['Y_' ssubsec '_' sreg]);

                % aggregate output
                strys.(['Q_' ssubsec]) = strys.(['Q_' ssubsec]) + strys.(['P_D_' ssubsec '_' sreg]) / strys.(['P_D_' ssubsec]) * strys.(['Q_' ssubsec '_' sreg]);

                % aggregate inermediate input
                strys.(['Q_I_' ssubsec]) = strys.(['Q_I_' ssubsec]) + strys.(['Q_I_' ssubsec '_' sreg]);
            end

            % compute sub sectoral exports
            strys.(['X_' ssubsec]) = strys.(['Q_' ssubsec]) * strpar.(['phiX_' ssubsec '_p']);

            strys.(['GA_direct_' ssubsec]) = 0;
            for icosecm = 1:strpar.inbsectors_p
                ssecm = num2str(icosecm);
                iasubsecm = strpar.(['substart_' ssecm '_p']):strpar.(['subend_' ssecm '_p']);
                for icosubsecm = iasubsecm
                    ssubsecm = num2str(icosubsecm);
                    for icoreg = 1:strpar.inbregions_p
                        sreg = num2str(icoreg);
                        if strpar.(['iGA_' ssubsecm '_p']) == icosubsec
                            strys.(['K_A_' ssubsecm '_' sreg]) = strexo.(['exo_GA_' ssubsecm '_' sreg]) * strpar.Y0_p / (strys.P * strpar.(['P_D_' ssubsec '_p']));
                            strys.(['G_A_' ssubsecm '_' sreg]) = strpar.(['deltaKA_' ssubsecm '_' sreg '_p']) * strys.(['K_A_' ssubsecm '_' sreg]);
                        end
                        if strpar.(['iIAP_' ssubsecm '_p']) == icosubsec
                            strys.(['K_AP_' ssubsecm '_' sreg]) = strexo.(['exo_IAP_' ssubsecm '_' sreg]) * strpar.Y0_p / (strys.P * strpar.(['P_D_' ssubsec '_p']));
                            strys.(['I_AP_' ssubsecm '_' sreg]) = strpar.(['deltaKA_' ssubsecm '_' sreg '_p']) * strys.(['K_AP_' ssubsecm '_' sreg]);
```

```
                        end

                        strys.(['GA_direct_' ssubsec]) = strys.(['GA_direct_' ssubsec]) + (strpar.(['iGA_' ssubsecm '_p'])==icosubsec) * strys.(['G_A_' ssubsecm '_' sreg]) + (strpar.(['iIAP_' ssubsecm '_p'])==icosubsec) * strys.(['I_AP_' ssubsecm '_' sreg]);
                    end
                end
            end

            % compute sub sectoral output used domestically
            strys.(['Q_D_' ssubsec]) = strys.(['Q_' ssubsec])   strys.(['X_' ssubsec])   strys.(['GA_direct_' ssubsec]) * strys.P   (strpar.iGAH_p == icosubsec) * strys.G_A_DH * strys.P   (strpar.iIAPH_p == icosubsec) * strys.I_AP_DH * strys.P;

            % compute sub sectoral exports share
            strys.(['D_X_' ssubsec]) = strys.(['X_' ssubsec]) / strys.(['Q_' ssubsec]);

            % update exports share parameter
            strpar.(['D_X_' ssubsec '_p']) = strys.(['X_' ssubsec]) * (strys.(['P_D_' ssubsec])/strys.(['P_M_' ssubsec]))^(strpar.etaX_p) ;


        end
    end
    for icosec = 1:strpar.inbsectors_p
        ssec = num2str(icosec);

        % initiliaze sectoral aggregate investment
        strys.(['I_' ssec]) = 0;

        for icoreg = 1:strpar.inbregions_p
            sreg = num2str(icoreg);

            % aggregate sectoral aggregate investment
            strys.(['I_' ssec]) = strys.(['I_' ssec]) + strys.(['I_' ssec '_' sreg]) ;
        end

        % initialize sectoral aggregate output
        strys.(['Q_A_' ssec]) = 0;

        % initialize sectoral aggregate price level
        strys.(['P_A_' ssec]) = 0;


        for icosubsec = strpar.(['substart_' ssec '_p']):strpar.(['subend_' ssec '_p'])
            ssubsec = num2str(icosubsec);
            temp= 0;
            % compute auxiliary expression to compute distribution
            % parameters across subsectors in one sector (denominator)
            tempdenom = (strys.(['P_D_' ssubsec]) /((strys.(['Q_D_' ssubsec]))^(1/strpar.(['etaQA' '_' ssec '_p']))))^(strpar.(['etaQA' '_' ssec '_p']));
            for icosubsecm = strpar.(['substart_' ssec '_p']):strpar.(['subend_' ssec '_p'])
                    ssubsecm = num2str(icosubsecm);
                    % compute auxiliary expression to compute distribution
                    % parameters across subsectors in one sector (numerator)
                    tempnum = (strys.(['P_D_' ssubsecm]) /((strys.(['Q_D_' ssubsecm]))^(1/strpar.(['etaQA' '_' ssec '_p']))))^(strpar.(['etaQA' '_' ssec '_p']));
                    % compute inverse distribution parameters across subsectors in one sector
                    temp = temp + tempnum / tempdenom;
            end

            % compute distribution parameters across subsectors in one sector
            strpar.(['omegaQ_' ssubsec '_p']) = 1/temp;

            % initialize subsectoral capital stock
            strys.(['K_' ssubsec]) = 0;

            % initialize subsectoral wage level
            strys.(['W_' ssubsec]) = 0;

            for icoreg = 1:strpar.inbregions_p
                sreg = num2str(icoreg);
                % aggregate  subsectoral capital stock
                strys.(['K_' ssubsec]) = strys.(['K_' ssubsec]) + strys.(['P_' ssubsec '_' sreg]) / strys.P * strys.(['K_' ssubsec '_' sreg]) ;

                % aggregate  subsectoral wages
                strys.(['W_' ssubsec]) = strys.(['W_' ssubsec]) + strys.(['N_' ssubsec '_' sreg]) / strys.(['N_' ssubsec]) * strys.(['W_' ssubsec '_' sreg]) ;

            end
```

```
            % aggregate  sectoral output
            strys.(['Q_A_' ssec]) = strys.(['Q_A_' ssec]) + strpar.(['omegaQ_' ssubsec '_p'])
                ^(1/strpar.(['etaQA' '_' ssec '_p'])) * strys.(['Q_D_' ssubsec])^((strpar.(['
                etaQA' '_' ssec '_p']) 1)/strpar.(['etaQA' '_' ssec '_p']));

            % aggregate  sectoral price level
            strys.(['P_A_' ssec]) = strys.(['P_A_' ssec]) + strpar.(['omegaQ_' ssubsec '_p'])
                * strys.(['P_D_' ssubsec])^(1   strpar.(['etaQA' '_' ssec '_p']));
        end

        % aggregate  sectoral price level
        strys.(['P_A_' ssec]) = strys.(['P_A_' ssec])^(1/(1   strpar.(['etaQA' '_' ssec '_p'])
            ));

        % aggregate  sectoral price level
        strys.(['Q_A_' ssec]) = strys.(['Q_A_' ssec])^(strpar.(['etaQA_' ssec '_p'])/(strpar
            .(['etaQA' '_' ssec '_p'])   1));

        % initialize  subsectoral capital stock
        strys.(['K_' ssubsec]) = 0;

        % initialize  subsectoral wages
        strys.(['W_' ssubsec]) = 0;

        for icoreg = 1:strpar.inbregions_p
            sreg = num2str(icoreg);
            % aggregate  subsectoral capital stock
            strys.(['K_' ssubsec]) = strys.(['K_' ssubsec]) + strys.(['P_' ssubsec '_' sreg])
                / strys.P * strys.(['K_' ssubsec '_' sreg]) ;

            % aggregate  subsectoral wages
            strys.(['W_' ssubsec]) = strys.(['W_' ssubsec]) + strys.(['N_' ssubsec '_' sreg])
                / strys.(['N_' ssubsec]) * strys.(['W_' ssubsec '_' sreg]) ;

        end
    end
    for icosec = 1:strpar.inbsectors_p
        ssec = num2str(icosec);
        % compute sectoral distribution parameters
        tempdenom = (strys.(['P_A_' ssec]) /((strys.(['Q_A_' ssec]))^( 1/strpar.etaQ_p)))^(
            strpar.etaQ_p);

        temp= 0;

        for icosecm = 1:strpar.inbsectors_p
            ssecm = num2str(icosecm);
            % compute sectoral distribution parameters
            tempnum = (strys.(['P_A_' ssecm]) /((strys.(['Q_A_' ssecm]))^( 1/strpar.etaQ_p)))
                ^(strpar.etaQ_p);

            % compute sectoral distribution parameters
            temp = temp + tempnum / tempdenom;

        end
        % compute sectoral distribution parameters
        strpar.(['omegaQA_' ssec '_p']) = 1/temp;
    end

    % compute domestic price level
    strys.P_D = 0;
    for icosec = 1:strpar.inbsectors_p
        ssec = num2str(icosec);
        strys.P_D = strys.P_D + strpar.(['omegaQA_' ssec '_p']) * strys.(['P_A_' ssec])^(1
            strpar.etaQ_p) ;
    end
    strys.P_D = strys.P_D^(1/(1   strpar.etaQ_p));

    % compute aggregates
    [strys, strpar, strexo] = ComputeAggregates(strys, strpar, strexo);

    % compute import price level
    strys.P_M = strpar.P0_M_p;

    % compute imports
    strys.M = strpar.phiM_p * strys.Q * strys.P_D / strys.P_M;

    % compute used products
    strys.Q_U = (strys.M * strys.P_M + strys.Q_D * strys.P_D)/strys.P;

    % compute distribution parameter for imports
    strpar.omegaF_p = strys.M * strys.P_M^strpar.etaF_p / (strys.M * strys.P_M^strpar.etaF_p +
        strys.Q_D * strys.P_D^strpar.etaF_p);

```

```
    % compute subsector imports and import prices
    for icosec = 1:strpar.inbsectors_p
        ssec = num2str(icosec);

        for icosubsec = strpar.(['substart_' ssec '_p']):strpar.(['subend_' ssec '_p'])
            ssubsec = num2str(icosubsec);

            if icosec == strpar.inbsectors_p && icosubsec == strpar.(['subend_' ssec '_p'])

                temp = strys.P_M^(strpar.etaM_p  1);

                for icosecm = 1:strpar.inbsectors_p
                    ssecm = num2str(icosecm);

                    if icosecm < strpar.inbsectors_p
                        for icosubsecm = strpar.(['substart_' ssecm '_p']):strpar.(['subend_' ssecm '_p'])
                            ssubsecm = num2str(icosubsecm);

                            temp = temp  strpar.(['phiM_' ssubsecm '_p']) * strys.(['P_M_' ssubsecm])^(strpar.etaM_p 1);

                        end
                    else
                        for icosubsecm = strpar.(['substart_' ssecm '_p']):(strpar.(['subend_' ssecm '_p']) 1)
                            ssubsecm = num2str(icosubsecm);

                            temp = temp  strpar.(['phiM_' ssubsecm '_p']) * strys.(['P_M_' ssubsecm])^(strpar.etaM_p 1);

                        end
                    end
                end
                strys.(['P_M_'  ssubsec]) = (temp / strpar.(['phiM_' ssubsec '_p']))^(1/(strpar.etaM_p 1));

            else
                strys.(['P_M_'  ssubsec]) = 0.9.*strys.P_M;%strpar.(['P_M_' ssec '_p']);

            end
            strpar.(['P_M_'  ssubsec '_p']) = strys.(['P_M_'  ssubsec]);

            strys.(['M_' ssubsec]) = strpar.(['phiM_' ssubsec '_p']) * strys.M * strys.P_M / strys.(['P_M_' ssubsec]);
        end
    end

    % compute distribution parameter for subsector imports
    for icosec = 1:strpar.inbsectors_p
        ssec = num2str(icosec);
        for icosubsec = strpar.(['substart_' ssec '_p']):strpar.(['subend_' ssec '_p'])
            ssubsec = num2str(icosubsec);

            temp = 0;

            tempdenom = strys.(['P_M_' ssubsec])^(strpar.etaM_p)  * strys.(['M_' ssubsec]);

            for icosecm = 1:strpar.inbsectors_p
                ssecm = num2str(icosecm);
                for icosubsecm = strpar.(['substart_' ssecm '_p']):strpar.(['subend_' ssecm '_p'])
                    ssubsecm = num2str(icosubsecm);

                    tempnum = strys.(['P_M_' ssubsecm])^(strpar.etaM_p)  * strys.(['M_' ssubsecm]);

                    temp = temp + tempnum / tempdenom;
                end
            end

            strpar.(['omegaM_' ssubsec '_p']) = 1/temp;

        end
    end

    % net exports
    strys.NX = (strys.P_D * strys.X  strys.P_M * strys.M)/strys.P;

    strpar.NX0_p = strys.NX/strys.Y;

    % domesitcally used products
    strys.Q_U = (strys.M * strys.P_M + strys.Q_D * strys.P_D)/strys.P;
```

```

    % compute tax income
    [strys,strpar, strexo] = TaxIncome(strys,strpar, strexo);

    % foreign debt / (B > 0 debitor vs. B < 0 creditor)
    strys.B =  strys.NX/strys.rf   strys.BG;

    % lagrange multiplier for houses
    strys.omegaH = strys.PH * (1 + strys.tauH);

    % house prices
    strys.PH = strpar.sH_p * strys.P * strys.Y / (strpar.deltaH_p * strys.H * (1 + strys.tauH));

    % consumption
    strys.C = ((strys.P_D / strys.P * strys.Q   strys.NX   strys.Q_I    strys.I   strys.wagetax    strys.capitaltax    strys.privateadaptationcost / strys.P   strys.PH / strys.P * strys.H * strpar.deltaH_p * (1 + strys.tauH) + strys.rf * strys.BG) / (1 + strys.tauC));

    % auxiliary variable to compute gamma
    tempgam = strys.H * strys.PH * (1 + strys.tauH) / (strys.C * strys.P * (1 + strys.tauC)) * (1   strpar.beta_p * (1   strpar.deltaH_p)) / (strpar.beta_p);

    % preference parameter for houses to ensure housing share
    strpar.gamma_p = tempgam / (1 + tempgam);

    % house price level
    strpar.PH0_p = strys.PH;

    % damages to houses induced by climate change
    strys.DH = strexo.exo_DH * strpar.Y0_p /strys.PH;

    % Lagrange multiplier of budget constraint HH
    strys.lambda = (1 strpar.gamma_p) * (strys.C/strys.PoP)^( strpar.gamma_p) * (strys.H/strys.PoP)^strpar.gamma_p * ((strys.C/strys.PoP)^(1 strpar.gamma_p) * (strys.H/strys.PoP)^strpar.gamma_p)^( strpar.sigmaC_p) / (strys.P * (1 + strys.tauC));

    % investment into housing
    strys.IH = strpar.deltaH_p * strys.H;

    % government expenditure
    strys.G = (strys.wagetax + strys.capitaltax + strys.tauC * strys.C + strys.tauH * strys.PH/strys.P * strys.IH)   strys.rf * strys.BG   strys.adaptationcost;

    % public capital stock
    strys.KG = strys.G / strpar.deltaKG_p;

    %% compute labour disutlity parameters
    for icosec = 1:strpar.inbsectors_p
        ssec = num2str(icosec);

        for icoreg = 1:strpar.inbregions_p
            sreg = num2str(icoreg);

            for icosubsec = strpar.(['substart_' ssec '_p']):strpar.(['subend_' ssec '_p'])
                ssubsec = num2str(icosubsec);

                strpar.(['phiL_' ssubsec '_' sreg '_p']) =  (1   strys.tauNH) * strys.(['W_' ssubsec '_' sreg]) * strys.lambda / (strys.(['A_N_' ssubsec '_' sreg]) * strys.(['N_' ssubsec '_' sreg])^(strpar.sigmaL_p));

                strpar.(['A_' ssubsec '_' sreg '_p']) = strys.(['A_' ssubsec '_' sreg]) ./ (strys.KG^strpar.phiG_p * exp(strexo.(['exo_' ssubsec '_' sreg])));

            end
        end
    end
    % check initial guess for price levle and implied one
    fval_vec = 1   strys.P / ((1   strpar.omegaF_p) * strys.P_D^(1   strpar.etaF_p) + (strpar.omegaF_p) * strys.P_M^(1   strpar.etaF_p))^(1/(1   strpar.etaF_p));

end
```

E Steady state calculation of DGE-CRED model for the Baseline and Climate Change Scenarios

```matlab
function [fval_vec, strys, strexo] = FindK(x, strys, strexo, strpar)
    % function [fval_vec, strys] = FindK(x, strys, strexo, strpar)
    % finds capital stock vector to fulfill the static equations of the
    % model
    % Inputs:
    %     x          [vector]       vector of initial values for the steady
    %                               state of the regional and sectoral capital
    %                               stock
    %     strys      [structure]    structure containing all endogeonous
    %                               variables of the model
    %     strexo     [structure]    structure containing all exogeonous
    %                               variables of the model
    %     strpar     [structure]    structure containing all parameters of the
    %                               model
    %
    % Output:
    %     fval_vec   [vector]       residuals of regional and sector specific
    %                               for FOC of Households with respect to
    %                               regional labour
    %     strys      [structure]    see inputs
    %     strexo     [structure]    see inputs

    % get maximum number of eectors
    strpar.sMaxsec = num2str(strpar.inbsectors_p);

    % get guesses for the capital stock
    istart = 1;

    iend = strpar.(['subend_' strpar.sMaxsec '_p'])*strpar.inbregions_p;

    x_start_vec_1 = x(istart:iend);

    % get guesses for intermediate production
    istart = (strpar.(['subend_' strpar.sMaxsec '_p'])*strpar.inbregions_p+1);

    iend   = (2*strpar.(['subend_' strpar.sMaxsec '_p'])*strpar.inbregions_p);

    x_start_vec_2 = x(istart:iend);

    % get guesses for exports
    istart = (2*strpar.(['subend_' strpar.sMaxsec '_p'])*strpar.inbregions_p)+1;

    iend   = (2*strpar.(['subend_' strpar.sMaxsec '_p'])*strpar.inbregions_p)+strpar.(['
        subend_' strpar.sMaxsec '_p']);

    x_start_vec_4 = x(istart:iend);

    % get guess for total imports
    strys.M = x((2*strpar.(['subend_' strpar.sMaxsec '_p'])*strpar.inbregions_p)+strpar.(['
        subend_' strpar.sMaxsec '_p'])+1);

    % compute foreing interest rate
    strys.rf = strpar.rf0_p + strexo.exo_rf;

    % assign regional climate variables
    for icoreg = 1:strpar.inbregions_p
        sreg = num2str(icoreg);
        for sClimateVar = strpar.casClimatevarsRegional
            strys.([char(sClimateVar) '_' sreg]) = strpar.([char(sClimateVar) '0_' sreg '_p'])
                + strexo.(['exo_' char(sClimateVar) '_' sreg]);

        end
    end
    for sClimateVar = strpar.casClimatevarsNational
        strys.(char(sClimateVar)) = strpar.([char(sClimateVar) '0_p']) + strexo.(['exo_' char(
            sClimateVar)]);

    end

    % define regional price level
    strys.P = strpar.P0_p .* exp(strexo.exo_P);

    % get import price
    if strpar.lEndogenousY_p == 0
        strys.P_M = x(end);

    else
        strys.P_M = strpar.P0_M_p + strexo.exo_M;
```

```
    end

    strys.P_M_1 = strys.P_M^(1   strpar.etaM_p);



    for icosec = 1:strpar.inbsectors_p
        ssec = num2str(icosec);
        for icosubsec = strpar.(['substart_' ssec '_p']):strpar.(['subend_' ssec '_p'])
            ssubsec = num2str(icosubsec);
            if strpar.lCalibration_p == 2
                % get initial guesses for export shares
                strys.(['D_X_' ssubsec]) = x_start_vec_4(icosubsec);

            else
                % get initial guesses for exports
                strys.(['X_' ssubsec]) = x_start_vec_4(icosubsec);

            end

            if icosubsec > 1
                % compute import prices
                strys.(['P_M_' ssubsec]) = (strpar.(['P_M_' ssubsec '_p'])./ strpar.P0_M_p + strexo.(['exo_M_' ssubsec])) * strys.P_M;

                % re compute the first import price
                strys.P_M_1 = strys.P_M_1   strpar.(['omegaM_' ssubsec '_p']) * strys.(['P_M_' ssubsec])^(1   strpar.etaM_p);
            end

        end
    end

    strys.P_M_1 = (strys.P_M_1/strpar.omegaM_1_p)^(1/(1   strpar.etaM_p));

    % compute domestic price level
    strys.P_D = ((strys.P^(1   strpar.etaF_p)   strpar.omegaF_p * strys.P_M^(1   strpar.etaF_p)) / (1   strpar.omegaF_p))^(1/(1   strpar.etaF_p));

    % assign predetermined variables
    [strys,strpar, strexo] = AssignPredeterminedVariables(strys,strpar, strexo);

    %
    if strpar.lCalibration_p == 2

        [strys, strpar, strexo] = Initialize_FindK_ExogenousY(strys, strpar, strexo, x, x_start_vec_1, x_start_vec_2);

    else
        for icosec = 1:strpar.inbsectors_p
            ssec = num2str(icosec);
            for icosubsec = strpar.(['substart_' ssec '_p']):strpar.(['subend_' ssec '_p'])
                ssubsec = num2str(icosubsec);
                for icoreg = 1:strpar.inbregions_p
                    sreg = num2str(icoreg);
                    icovec = icoreg + (icosubsec 1)*strpar.inbregions_p;

                    strys.(['Q_I_' ssubsec '_' sreg]) = sqrt(real(x_start_vec_2(icovec)).^2);

                    strys.(['K_' ssubsec '_' sreg]) = sqrt(real(x_start_vec_1(icovec)).^2);
                end
            end
        end
        if strpar.phiG_p > 0
            if strpar.lEndogenousY_p == 0

                strys.G = x(end 1);
            else

                strys.G = x(end);
            end
        end
    end

    % public capital stock
    strys.KG = strys.G / strpar.deltaKG_p;


    %% calculate exogenous variables

    % population stock
    strys.PoP = strpar.PoP0_p * exp(strexo.exo_PoP);
```

```
    if strpar.lEndogenousY_p == 0
        % housing area
        strys.H  = (strpar.H0_p + strexo.exo_H) * strys.PoP;

    else
        % price per housing area
        strys.PH  = strpar.PH0_p * exp(strexo.exo_H);

    end

    % government expenditure to the housing area
    if strpar.iGAH_p == 0
        strys.G_A_DH = strexo.exo_G_A_DH * strpar.Y0_p / strpar.P0_p;
    else
        strys.G_A_DH = strexo.exo_G_A_DH * strpar.Y0_p / (strpar.P0_p * strpar.(['P_D_'
            num2str(strpar.iGAH_p) '_p']));
    end

    if strpar.iIAPH_p == 0
        strys.I_AP_DH = strexo.exo_I_AP_DH * strpar.Y0_p / strpar.P0_p;
    else
        strys.I_AP_DH = strexo.exo_I_AP_DH * strpar.Y0_p / (strpar.P0_p * strpar.(['P_D_'
            num2str(strpar.iIAPH_p) '_p']));
    end

    %% calculate sectoral and regional production factors and output
    for icosec = 1:strpar.inbsectors_p
        ssec = num2str(icosec);
        % compute sectoral rental rate for capital
        strys.(['r_' ssec]) = (1/strpar.beta_p   1 + strpar.delta_p)/(1   strys.tauKH);

        for icoreg = 1:strpar.inbregions_p
            sreg = num2str(icoreg);

            % compute sectoral and regional rental rate for capital
            strys.(['r_' ssec '_' sreg]) = (1/strpar.beta_p   1 + strpar.delta_p)/(1   strys.
                tauKH);

            for icosubsec = strpar.(['substart_' ssec '_p']):strpar.(['subend_' ssec '_p'])
                ssubsec = num2str(icosubsec);

                % auxiliary variable to define the degree of substitutability
                % between capital and labour in the sector
                rhotemp = ((strpar.(['etaNK_' ssubsec '_' sreg '_p']) 1)/strpar.(['etaNK_'
                    ssubsec '_' sreg '_p']));

                % compute sectoral and regional rental rate for capital
                strys.(['lambK_' ssubsec '_' sreg]) = 0;

                if strpar.lEndogenousY_p == 1
                    % compute regional and sub sectoral productivity
                    strys.(['A_' ssubsec '_' sreg]) = strpar.(['A_' ssubsec '_' sreg '_p']) *
                        exp(strexo.(['exo_' ssubsec '_' sreg])) * strys.KG^strpar.phiG_p;

                end

                if strpar.lEndogenousY_p == 1
                    % compute regional and sub sectoral labour productivity
                    strys.(['A_N_' ssubsec '_' sreg]) = strpar.(['A_N_' ssubsec '_' sreg '_p'
                        ]) * exp(strexo.(['exo_N_' ssubsec '_' sreg]));

                end

                rkgross = strys.(['r_' ssec '_' sreg]) * (1 + strys.(['tauKF_' ssubsec '_'
                    sreg]));

                if strpar.lCalibration_p == 2 % Baseline / exogenous Y
                    if strpar.(['etaNK_' ssubsec '_' sreg '_p']) ~= 1
                        % compute regional and sub sectoral productivity
                        strys.(['A_' ssubsec '_' sreg]) = (rkgross / (strpar.(['alphaK_'
                            ssubsec '_' sreg '_p'])^(1/ strpar.(['etaNK_' ssubsec '_' sreg '_p
                            '])) *  (strys.(['A_K_' ssubsec '_' sreg]) * (1   strys.(['D_'
                            ssubsec '_' sreg])))^rhotemp * (strys.(['K_' ssubsec '_' sreg])/
                            strys.(['Y_' ssubsec '_' sreg]))^( 1/strpar.(['etaNK_' ssubsec '_'
                             sreg '_p'])))))^(1/rhotemp);

                    else
                        % compute the capital stock
                        strys.(['K_' ssubsec '_' sreg]) = strpar.(['alphaK_' ssubsec '_' sreg
                            '_p']) * strys.(['Y_' ssubsec '_' sreg]) / rkgross;

                        % compute the gross wage
```

```
                    wgross = strpar.(['alphaN_' ssubsec '_' sreg '_p']) / strpar.(['alphaK_' ssubsec '_' sreg '_p']) * strys.(['K_' ssubsec '_' sreg]) / (strys.PoP * strys.(['N_' ssubsec '_' sreg])) * rkgross * strys.(['P_' ssubsec '_' sreg]);

                    % compute auxiliary variable to compute
                    % productivity
                    temp = (rkgross/(strpar.(['alphaK_' ssubsec '_' sreg '_p']) * strys.(['A_K_' ssubsec '_' sreg])))^strpar.(['alphaK_' ssubsec '_' sreg '_p']) * ...
                        (wgross/(strpar.(['alphaN_' ssubsec '_' sreg '_p']) * strys.(['A_N_' ssubsec '_' sreg]) * (1   strys.(['D_N_' ssubsec '_' sreg]))))^strpar.(['alphaK_' ssubsec '_' sreg '_p']));

                    % compute subsectoral and regional productivity
                    strys.(['A_' ssubsec '_' sreg]) = strys.(['P_' ssubsec '_' sreg]) / temp;

                end

                % recompute the exogenous disturbances to productivity
                % should be unneccary if everything is correct
                if strpar.lEndogenousY_p == 1
                    strexo.(['exo_' ssubsec '_' sreg]) = log(strys.(['A_' ssubsec '_' sreg]) / (strys.KG^strpar.phiG_p * strpar.(['A_' ssubsec '_' sreg '_p'])));

                else
                    strexo.(['exo_' ssubsec '_' sreg]) = log((strys.(['Y_' ssubsec '_' sreg]) .* strys.(['P_' ssubsec '_' sreg])/strys.P) ./ (strpar.Y0_p ./strpar.P0_p .* strpar.(['phiY0_' ssubsec '_' sreg '_p'])));

                end
                % compute exogenous labour productivity
                if strpar.(['etaNK_' ssubsec '_' sreg '_p']) ~= 1 % CES
                    temp1 = (strys.(['K_' ssubsec '_' sreg]) * rkgross^strpar.(['etaNK_' ssubsec '_' sreg '_p']) / (strpar.(['alphaK_' ssubsec '_' sreg '_p']) * strys.(['A_K_' ssubsec '_' sreg])^(strpar.(['etaNK_' ssubsec '_' sreg '_p']) 1) * (strys.(['A_' ssubsec '_' sreg]) * (1 strys.(['D_' ssubsec '_' sreg])))^(strpar.(['etaNK_' ssubsec '_' sreg '_p'])))))^rhotemp;

                    temp2 = strpar.(['alphaK_' ssubsec '_' sreg '_p'])^(1/strpar.(['etaNK_' ssubsec '_' sreg '_p'])) * strys.(['A_K_' ssubsec '_' sreg])^rhotemp * strys.(['K_' ssubsec '_' sreg])^rhotemp;

                    temp = ((temp1   temp2) / (strpar.(['alphaN_' ssubsec '_' sreg '_p'])^(1/strpar.(['etaNK_' ssubsec '_' sreg '_p'])) * (strys.PoP .* strys.(['N_' ssubsec '_' sreg]))^rhotemp))^(1/rhotemp);

                    strys.(['A_N_' ssubsec '_' sreg]) = temp / (1   strys.(['D_N_' ssubsec '_' sreg]));

                    if strpar.lEndogenousY_p == 1
                        strexo.(['exo_N_' ssubsec '_' sreg]) = log(strys.(['A_N_' ssubsec '_' sreg])/strpar.(['A_N_' ssubsec '_' sreg '_p']));

                    else
                        strexo.(['exo_N_' ssubsec '_' sreg]) = log(strys.(['N_' ssubsec '_' sreg])/(strpar.(['phiN0_' ssubsec '_' sreg '_p'])*strpar.N0_p));

                    end
                else % Cobb Douglas
                    if strpar.lEndogenousY_p == 1
                        strexo.(['exo_N_' ssubsec '_' sreg]) = log(strys.(['A_N_' ssubsec '_' sreg])/strpar.(['A_N_' ssubsec '_' sreg '_p']));

                    end
                end
            else  % Climate Change Scenarios / endogenous Y
                if strpar.(['etaNK_' ssubsec '_' sreg '_p']) ~= 1
                    temp1 = (strys.(['K_' ssubsec '_' sreg]) * rkgross^strpar.(['etaNK_' ssubsec '_' sreg '_p']) / (strpar.(['alphaK_' ssubsec '_' sreg '_p']) * strys.(['A_K_' ssubsec '_' sreg])^(strpar.(['etaNK_' ssubsec '_' sreg '_p']) 1) * (strys.(['A_' ssubsec '_' sreg]) * (1 strys.(['D_' ssubsec '_' sreg])))^(strpar.(['etaNK_' ssubsec '_' sreg '_p'])))))^rhotemp;

                    temp2 = strpar.(['alphaK_' ssubsec '_' sreg '_p'])^(1/strpar.(['etaNK_' ssubsec '_' sreg '_p'])) * strys.(['A_K_' ssubsec '_' sreg])^rhotemp * strys.(['K_' ssubsec '_' sreg])^rhotemp;

```

```
                    temp = ((temp1   temp2) / (strpar.(['alphaN_' ssubsec '_' sreg '_p'])^(1/strpar.(['etaNK_' ssubsec '_' sreg '_p']))))^(1/rhotemp);

                    if strpar.lEndogenousY_p == 1
                        % compute labour
                        strys.(['N_' ssubsec '_' sreg]) = temp / (strys.PoP * (1   strys.(['D_N_' ssubsec '_' sreg])) * strys.(['A_N_' ssubsec '_' sreg]));

                    else
                        % compute labour productivity
                        strys.(['A_N_' ssubsec '_' sreg]) = temp / (strys.PoP * (1   strys.(['D_N_' ssubsec '_' sreg])) * strys.(['N_' ssubsec '_' sreg]));

                    end
                else
                    % compute labour demand
                    strys.(['N_' ssubsec '_' sreg]) = (strys.(['K_' ssubsec '_' sreg]) * rkgross / (strpar.(['alphaK_' ssubsec '_' sreg '_p']) * strys.(['A_' ssubsec '_' sreg]) *  (1   strys.(['D_' ssubsec '_' sreg])) * (strys.(['A_K_' ssubsec '_' sreg]) * ...
                                                        strys.(['K_' ssubsec '_' sreg]))^strpar.(['alphaK_' ssubsec '_' sreg '_p'])))^(1/strpar.(['alphaN_' ssubsec '_' sreg '_p'])) / (strys.(['A_N_' ssubsec '_' sreg]) * (1   strys.(['D_N_' ssubsec '_' sreg])) * strys.PoP);


                end

            end
            if strpar.(['etaNK_' ssubsec '_' sreg '_p']) ~= 1 % CES
                if strpar.lEndogenousY_p == 1
                    % compute gross vlaue added
                    strys.(['Y_' ssubsec '_' sreg]) = strys.(['A_' ssubsec '_' sreg]) * (1   strys.(['D_' ssubsec '_' sreg])) * (strpar.(['alphaK_' ssubsec '_' sreg '_p'])^(1/strpar.(['etaNK_' ssubsec '_' sreg '_p'])) * (strys.(['A_K_' ssubsec '_' sreg]) * strys.(['K_' ssubsec '_' sreg]))^rhotemp + strpar.(['alphaN_' ssubsec '_' sreg '_p'])^(1/strpar.(['etaNK_' ssubsec '_' sreg '_p'])) * (strys.PoP * strys.(['A_N_' ssubsec '_' sreg]) * (1   strys.(['D_N_' ssubsec '_' sreg])) * strys.(['N_' ssubsec '_' sreg]))^rhotemp)^(1/rhotemp);

                else
                    % compute productivity
                    strys.(['A_' ssubsec '_' sreg]) = strys.(['Y_' ssubsec '_' sreg]) /((1   strys.(['D_' ssubsec '_' sreg])) * (strpar.(['alphaK_' ssubsec '_' sreg '_p'])^(1/strpar.(['etaNK_' ssubsec '_' sreg '_p'])) * (strys.(['A_K_' ssubsec '_' sreg]) * strys.(['K_' ssubsec '_' sreg]))^rhotemp + strpar.(['alphaN_' ssubsec '_' sreg '_p'])^(1/strpar.(['etaNK_' ssubsec '_' sreg '_p'])) * (strys.PoP * strys.(['A_N_' ssubsec '_' sreg]) * (1   strys.(['D_N_' ssubsec '_' sreg])) * strys.(['N_' ssubsec '_' sreg]))^rhotemp)^(1/rhotemp));

                end
            else
                if strpar.lEndogenousY_p == 1
                    % compute gross vlaue added % Cobb Douglas
                    strys.(['Y_' ssubsec '_' sreg]) = strys.(['A_' ssubsec '_' sreg]) * (1   strys.(['D_' ssubsec '_' sreg])) *  (strys.(['A_K_' ssubsec '_' sreg]) * strys.(['K_' ssubsec '_' sreg]))^strpar.(['alphaK_' ssubsec '_' sreg '_p']) * (strys.PoP * strys.(['A_N_' ssubsec '_' sreg]) * (1   strys.(['D_N_' ssubsec '_' sreg])) * strys.(['N_' ssubsec '_' sreg]))^strpar.(['alphaN_' ssubsec '_' sreg '_p']);

                else
                    % compute productivity
                    strys.(['A_' ssubsec '_' sreg]) = strys.(['Y_' ssubsec '_' sreg]) / ((1   strys.(['D_' ssubsec '_' sreg])) *  (strys.(['A_K_' ssubsec '_' sreg]) * strys.(['K_' ssubsec '_' sreg]))^strpar.(['alphaK_' ssubsec '_' sreg '_p']) * (strys.PoP * strys.(['A_N_' ssubsec '_' sreg]) * (1   strys.(['D_N_' ssubsec '_' sreg])) * strys.(['N_' ssubsec '_' sreg]))^strpar.(['alphaN_' ssubsec '_' sreg '_p']));

                end
            end
            % compute substitutability between intermediate goods and
            % gross value added
```

```
                rhotemp = (strpar.(['etaI_' ssubsec '_p'])  1)/strpar.(['etaI_' ssubsec '_p']);

                % compute outputs
                strys.(['Q_' ssubsec '_' sreg]) = (strpar.(['omegaQI_' ssubsec '_' sreg '_p'])^(1/strpar.(['etaI_' ssubsec '_p'])) * strys.(['Q_I_' ssubsec '_' sreg])^rhotemp + ...
                                                (1  strpar.(['omegaQI_' ssubsec '_' sreg '_p']))^(1/strpar.(['etaI_' ssubsec '_p'])) * strys.(['Y_' ssubsec '_' sreg])^rhotemp)^(1/rhotemp);
            end
        end
        % initiliaze aggregate sector production
        strys.(['Q_A_' ssec]) = 0;

        % compute subsitutability between different sbsectors in the sector
        rhotemp = (strpar.(['etaQA_' ssec '_p']) 1)/strpar.(['etaQA_' ssec '_p']);

        for icosubsec = strpar.(['substart_' ssec '_p']):strpar.(['subend_' ssec '_p'])
            ssubsec = num2str(icosubsec);
            % initiliaze aggregate subsector production
            strys.(['Q_' ssubsec]) = 0;

            for icoreg = 1:strpar.inbregions_p
                sreg = num2str(icoreg);
                % compute subsector production
                strys.(['Q_' ssubsec]) = strys.(['Q_' ssubsec]) + strpar.(['omegaQ_' ssubsec '_' sreg '_p'])^(1/strpar.(['etaQ_' ssubsec '_p'])) * (strys.(['Q_' ssubsec '_' sreg]))^((strpar.(['etaQ_' ssubsec '_p']) 1)/strpar.(['etaQ_' ssubsec '_p']));

            end
            % compute subsector production
            strys.(['Q_' ssubsec]) = strys.(['Q_' ssubsec])^(strpar.(['etaQ_' ssubsec '_p'])/(strpar.(['etaQ_' ssubsec '_p']) 1));

            % compute direct adaptation expenditures in the current subsector
            strys.(['GA_direct_' ssubsec]) = 0;
            for icosecm = 1:strpar.inbsectors_p
                ssecm = num2str(icosecm);
                iasubsecm = strpar.(['substart_' ssecm '_p']):strpar.(['subend_' ssecm '_p']);
                for icosubsecm = iasubsecm
                    ssubsecm = num2str(icosubsecm);
                    for icoreg = 1:strpar.inbregions_p
                        sreg = num2str(icoreg);
                        strys.(['GA_direct_' ssubsec]) = strys.(['GA_direct_' ssubsec]) + (strpar.(['iGA_' ssubsecm '_p'])==icosubsec) * strys.(['G_A_' ssubsecm '_' sreg]) + (strpar.(['iIAP_' ssubsecm '_p'])==icosubsec) * strys.(['I_AP_' ssubsecm '_' sreg]);
                    end
                end
            end

            if strpar.lCalibration_p == 2
                % compute exports
                strys.(['X_' ssubsec]) = strys.(['Q_' ssubsec]) * strys.(['D_X_' ssubsec]);

            else
                % compute export share
                strys.(['D_X_' ssubsec]) = strys.(['X_' ssubsec]) / strys.(['Q_' ssubsec]);

            end

            % compute domestically used products
            strys.(['Q_D_' ssubsec]) = strys.(['Q_' ssubsec])  strys.(['X_' ssubsec])  (strpar.iIAPH_p == icosubsec) * strys.I_AP_DH * strys.P  (strpar.iGAH_p == icosubsec) * strys.G_A_DH * strys.P  strys.(['GA_direct_' ssubsec]) * strys.P;

            % aggregate sector production
            strys.(['Q_A_' ssec])  = strys.(['Q_A_' ssec]) + strpar.(['omegaQ_' ssubsec '_p'])^(1/strpar.(['etaQA_' ssec '_p'])) * strys.(['Q_D_' ssubsec])^rhotemp;
        end
        % aggregate sector production
        strys.(['Q_A_' ssec])  = strys.(['Q_A_' ssec])^(1/rhotemp);

    end

    % init domestically used products
    strys.Q_D = 0;

    % substituatibility between sectoral products
```

```
    rhotemp = (strpar.etaQ_p 1)/strpar.etaQ_p;

    for icosec = 1:strpar.inbsectors_p
        ssec = num2str(icosec);
        % aggregate domestically used products
        strys.Q_D  = strys.Q_D + strpar.(['omegaQA_' ssec '_p'])^(1/strpar.etaQ_p) * strys.(['Q_A_' ssec])^rhotemp;
    end

    % domestic output
    strys.Q_D = strys.Q_D^(1/rhotemp);

    % substituatibility between domestic and foreign products
    rhotemp = (strpar.etaF_p 1)/strpar.etaF_p;

    % domestically used output
    strys.Q_U = (strpar.omegaF_p^(1/strpar.etaF_p) * strys.M^rhotemp + (1   strpar.omegaF_p)^(1/strpar.etaF_p) * strys.Q_D^rhotemp)^(1/rhotemp);

    % domestic price level
    strys.P_D = (1   strpar.omegaF_p)^(1/strpar.etaF_p) * (strys.Q_D/strys.Q_U)^( 1/strpar.etaF_p) * strys.P;

    %% calculate sectoral and regional price indices and sectoral aggregates
    for icosec = 1:strpar.inbsectors_p
        ssec = num2str(icosec);
        % compute sectoral price level
        strys.(['P_A_' ssec]) = strpar.(['omegaQA_' ssec '_p'])^(1/strpar.etaQ_p) * (strys.(['Q_A_' ssec]) / strys.Q_D)^( 1/strpar.etaQ_p) * strys.P_D;

        % init sectoral capital stock
        strys.(['KH_' ssec]) = 0;

        for icosubsec = strpar.(['substart_' ssec '_p']):strpar.(['subend_' ssec '_p'])
            ssubsec = num2str(icosubsec);
            % compute sub sectoral imports
            strys.(['M_' ssubsec]) = strpar.(['omegaM_' ssubsec '_p']) * (strys.(['P_M_' ssubsec]) / strys.P_M)^( strpar.etaM_p) * strys.M;

            % init sub sectoral labour
            strys.(['N_' ssubsec]) = 0;

            % compute sub sectoral price level
            strys.(['P_D_' ssubsec]) = strpar.(['omegaQ_' ssubsec '_p'])^(1/strpar.(['etaQA_' ssec '_p'])) * (strys.(['Q_D_' ssubsec]) / strys.(['Q_A_' ssec]))^( 1/strpar.(['etaQA_' ssec '_p'])) * strys.(['P_A_' ssec]);strys.(['D_X_' ssubsec]);

            for icoreg = 1:strpar.inbregions_p
                sreg = num2str(icoreg);
                rhotemp = ((strpar.(['etaNK_' ssubsec '_' sreg '_p']) 1)/strpar.(['etaNK_' ssubsec '_' sreg '_p']));

                % compute sub sectoral and regional domestic price level
                strys.(['P_D_' ssubsec '_' sreg]) = strpar.(['omegaQ_' ssubsec '_' sreg '_p'])^(1/strpar.(['etaQ_' ssubsec '_p'])) * (strys.(['Q_' ssubsec '_' sreg]) / strys.(['Q_' ssubsec]))^( 1/strpar.(['etaQ_' ssubsec '_p'])) * strys.(['P_D_' ssubsec]);

                % compute sub sectoral and regional price level of primary
                % production factors
                strys.(['P_' ssubsec '_' sreg]) = (1   strpar.(['omegaQI_' ssubsec '_' sreg '_p']))^(1/strpar.(['etaI_' ssubsec '_p'])) * (strys.(['Y_' ssubsec '_' sreg]) / strys.(['Q_' ssubsec '_' sreg]))^( 1/strpar.(['etaI_' ssubsec '_p'])) * strys.(['P_D_' ssubsec '_' sreg]);

                % compute sub sectoral and regional wages
                strys.(['W_' ssubsec '_' sreg]) = strpar.(['alphaN_' ssubsec '_' sreg '_p'])^(1/strpar.(['etaNK_' ssubsec '_' sreg '_p'])) * (strys.(['A_' ssubsec '_' sreg]) * (1   strys.(['D_' ssubsec '_' sreg])) * strys.(['A_N_' ssubsec '_' sreg]) * (1   strys.(['D_N_' ssubsec '_' sreg])))^rhotemp * ((strys.(['N_' ssubsec '_' sreg]) * strys.PoP) / strys.(['Y_' ssubsec '_' sreg]))^( 1/strpar.(['etaNK_' ssubsec '_' sreg '_p']))*strys.(['P_' ssubsec '_' sreg]) / (1 + strys.(['tauNF_' ssubsec '_' sreg]));

                % aggregate sub sectoral labour
                strys.(['N_' ssubsec]) = strys.(['N_' ssubsec]) + strys.(['N_' ssubsec '_' sreg]);

            end

            % init sub sectoral capital stock
            strys.(['K_' ssubsec]) = 0;

```

```
            % init sub sectoral wages
            strys.(['W_' ssubsec]) = 0;

            % init intermediate subsectoral gross value added
            strys.(['Y_' ssubsec]) = 0;

            % init intermediate subsectoral products
            strys.(['Q_I_' ssubsec]) = 0;

            for icoreg = 1:strpar.inbregions_p
                sreg = num2str(icoreg);

                % aggregate sectoral and regional capital stock of households
                if icosubsec == strpar.(['substart_' ssec '_p'])
                    strys.(['KH_' ssec '_' sreg]) = 0;
                end

                % compute subsectoral capital sotck
                strys.(['K_' ssubsec]) = strys.(['K_' ssubsec]) + strys.(['P_' ssubsec '_'
                    sreg]) / strys.P * strys.(['K_' ssubsec '_' sreg]) ;

                % compute subsectoral wages
                strys.(['W_' ssubsec]) = strys.(['W_' ssubsec]) + strys.(['N_' ssubsec '_'
                    sreg]) / strys.(['N_' ssubsec]) * strys.(['W_' ssubsec '_' sreg]) ;

                % compute subsectoral gross value added
                strys.(['Y_' ssubsec]) = strys.(['Y_' ssubsec]) + strys.(['P_' ssubsec '_'
                    sreg]) * strys.(['Y_' ssubsec '_' sreg]) ;

                % compute aggregate subsectoral intermediate products demand
                strys.(['Q_I_' ssubsec]) = strys.(['Q_I_' ssubsec]) + strys.(['Q_I_' ssubsec '
                    _' sreg]) ;

                % compute sectoral and regional capital demand
                strys.(['KH_' ssec '_' sreg]) = strys.(['KH_' ssec '_' sreg]) + strys.(['P_'
                    ssubsec '_' sreg]) * strys.(['K_' ssubsec '_' sreg]) ./ strys.P;

                % compute sectoral and regional investment
                strys.(['I_' ssec '_' sreg]) = (strpar.delta_p) * strys.(['KH_' ssec '_' sreg
                    ]) + strys.(['D_KHelp_' ssec '_' sreg]);

                % compute aggregate sectoral capital stock
                strys.(['KH_' ssec]) = strys.(['KH_' ssec]) + strys.(['P_' ssubsec '_' sreg])
                    * strys.(['K_' ssubsec '_' sreg]) ./ strys.P;

            end
        end

        % init aggregate sectoral invesment
        strys.(['I_' ssec]) = 0;

        % compute aggregate sectoral invesment
        for icoreg = 1:strpar.inbregions_p
            sreg = num2str(icoreg);
            strys.(['I_' ssec]) = strys.(['I_' ssec]) + strys.(['I_' ssec '_' sreg]) ;
        end
    end

    % compute aggregates
    [strys, strpar, strexo] = ComputeAggregates(strys, strpar, strexo);

    % net exports
    strys.NX = (strys.P_D * strys.X   strys.P_M * strys.M)/strys.P;

    % products used domestically
    strys.Q_U = (strys.M * strys.P_M + strys.Q_D * strys.P_D)/strys.P;

    % compute tax income of the government
    [strys,strpar, strexo] = TaxIncome(strys,strpar, strexo);

    % define private net foreign asset position
    strys.B =  strys.NX/strys.rf  strys.BG;


    %% Households consumption level, FOC w.r.t housing and consumption
    strys.C = ((strys.P_D / strys.P * strys.Q   strys.NX   strys.Q_I   strys.I   strys.
        privateadaptationcost / strys.P   strys.wagetax   strys.capitaltax + strys.rf *
        strys.BG   strys.Y * strexo.exo_DH * (1 + strys.tauH)) / (1 + strys.tauC)) / (1 +
        strpar.gamma_p/(1  strpar.gamma_p) * strpar.deltaH_p * strpar.beta_p / (1 strpar.
        beta_p*(1 strpar.deltaH_p)));

    if strpar.lEndogenousY_p == 0
        % house prices
```

```
        strys.PH = (strpar.gamma_p/(1   strpar.gamma_p)  * strpar.beta_p / (1   strpar.beta_p * (1   strpar.deltaH_p)) * strys.C * strys.P * (1 + strys.tauC)) / (strys.H * (1 + strys.tauH));

    else
        % housing stock
        strys.H  = (strpar.gamma_p/(1   strpar.gamma_p)  * strpar.beta_p / (1   strpar.beta_p * (1   strpar.deltaH_p)) * strys.C * strys.P * (1 + strys.tauC)) / (strys.PH * (1 + strys.tauH));

    end

    % Lagrange multiplier for the evolution of the household stock
    strys.omegaH = strys.PH * (1 + strys.tauH);

    % damages to the housing stock
    strys.DH = strexo.exo_DH * strys.Y .* strys.P  /strys.PH;

    % investments into the housing stock
    strys.IH = strpar.deltaH_p * strys.H + strys.DH;

    % Lagrange multiplier for the budget constraint
    strys.lambda = (1 strpar.gamma_p) * (strys.C/strys.PoP)^( strpar.gamma_p) * (strys.H/strys.PoP)^strpar.gamma_p * ((strys.C/strys.PoP)^(1 strpar.gamma_p) * (strys.H/strys.PoP)^strpar.gamma_p)^( strpar.sigmaC_p) / (strys.P * (1 + strys.tauC));


    %% government budget constraint
    if strpar.phiG_p > 0
        fval_vec_G = 1   strys.G / ((strys.wagetax + strys.capitaltax + strys.tauC * strys.C + strys.tauH * strys.PH/strys.P * strys.IH)   strys.rf * strys.BG   strys.adaptationcost);

    else
        strys.G = (strys.wagetax + strys.capitaltax + strys.tauC * strys.C + strys.tauH * strys.PH/strys.P * strys.IH)   strys.rf * strys.BG   strys.adaptationcost;

        strys.KG = strys.G/strpar.deltaKG_p;

    end
    %% evaluate resiudals for:
    %   HH FOC w.r.t. labour in each region and subsector
    %   Firms FOC w.r.t. intermediate goods in each region and subsector
    %   Export demand for each region and subsector

    strpar.sMaxsec = num2str(strpar.inbsectors_p);

    fval_vec_1 = nan(strpar.(['subend_' strpar.sMaxsec '_p'])*strpar.inbregions_p,1);

    fval_vec_2 = nan(strpar.(['subend_' strpar.sMaxsec '_p'])*strpar.inbregions_p,1);

    fval_vec_4 = nan(strpar.(['subend_' strpar.sMaxsec '_p']),1);

    for icosec = 1:strpar.inbsectors_p
        ssec = num2str(icosec);

        strys.(['omegaI_' ssec]) = strys.P;

        for icosubsec = strpar.(['substart_' ssec '_p']):strpar.(['subend_' ssec '_p'])
            ssubsec = num2str(icosubsec);

            lhs = strys.(['X_' ssubsec]);
            rhs = (strpar.(['D_X_' ssubsec '_p']) + strexo.(['exo_X_' ssubsec])) * (strys.(['P_D_' ssubsec])/strys.(['P_M_' ssubsec]))^( strpar.etaX_p);
            fval_vec_4(icosubsec) = 1   lhs/rhs;

            for icoreg = 1:strpar.inbregions_p
                sreg = num2str(icoreg);

                icovec = icoreg + strpar.inbregions_p * (icosubsec 1);

                lhs = (1   strys.tauNH) * strys.(['W_' ssubsec '_' sreg]) * strys.lambda;

                rhs = strpar.(['phiL_' ssubsec '_' sreg '_p']) * strys.(['A_N_' ssubsec '_' sreg]) * (strys.(['N_' ssubsec '_' sreg]))^(strpar.sigmaL_p);

                fval_vec_1(icovec) = 1   lhs./rhs;

                lhs = strys.P / strys.(['P_D_' ssubsec '_' sreg]);

                rhs = (strpar.(['omegaQI_' ssubsec '_' sreg '_p']))^(1/strpar.(['etaI_' ssubsec '_p'])) * (strys.(['Q_I_' ssubsec '_' sreg])/strys.(['Q_' ssubsec '_' sreg]))^( 1/strpar.(['etaI_' ssubsec '_p']));
```

```
                fval_vec_2(icovec) = 1   lhs./rhs;
            end

        end
    end

    lhs = strys.P_M;

    rhs = strpar.omegaF_p^(1/strpar.etaF_p) * (strys.M/strys.Q_U)^(1/strpar.etaF_p) * strys.P
        ;

    fval_vec_3 = 1   lhs./rhs;

    if strpar.phiG_p > 0
        fval_vec = [fval_vec_1(:); fval_vec_2(:); fval_vec_3(:); fval_vec_G; fval_vec_4(:)];

    else
        fval_vec = [fval_vec_1(:); fval_vec_2(:); fval_vec_3(:); fval_vec_4(:)];

    end
    if strpar.lEndogenousY_p == 0
        % evaluation of the net export to gross value added ratio
        fval_vec_NX = strys.NX./strys.Y   strpar.NX0_p;

        fval_vec = [fval_vec; fval_vec_NX];

   end
end

function [strys, strpar, strexo] = Initialize_FindK_ExogenousY(strys, strpar, strexo, x,
    x_start_vec_1, x_start_vec_2);
    % function [fval_vec,strys] =
    % Initialize_FindK_ExogenousY(strys, strpar, strexo, x, x_start_vec_1,
    %                              x_start_vec_2)
    % finds capital stock vector to fulfill the static equations of the
    % model
    % Inputs:
    %    x          [vector]     vector of initial values for the steady
    %                            state of the regional and sectoral capital
    %                            stock
    %    strys      [structure]  structure containing all endogeonous
    %                            variables of the model
    %    strexo     [structure]  structure containing all exogeonous
    %                            variables of the model
    %    strpar     [structure]  structure containing all parameters of the
    %                            model
    %
    % Output:
    %    fval_vec   [vector]     residuals of regional and sector specific
    %                            for FOC of Households with respect to
    %                            regional labour
    %    strys      [structure]  see inputs
    %    strexo     [structure]  see inputs

    % terminal labour supply
    strys.N = strpar.NT_p;

    % terminal GDP
    strys.Y = strpar.YT_p;

    % init output
    strys.Q = 0;

    % init domestically used output
    strys.Q_D = 0;

    % imports
    strys.M = x((2*strpar.(['subend_' strpar.sMaxsec '_p'])*strpar.inbregions_p)+strpar.(['
        subend_' strpar.sMaxsec '_p'])+1) *strys.Y;

    for icosec = 1:strpar.inbsectors_p
        ssec = num2str(icosec);
        % init sectoral expenditure
        strpar.(['phiQA_' ssec '_p']) = 0;

        for icosubsec = strpar.(['substart_' ssec '_p']):strpar.(['subend_' ssec '_p'])
            ssubsec = num2str(icosubsec);

            % init sub sectoral expenditure
            strpar.(['phiQ_' ssubsec '_p']) = 0;

            for icoreg = 1:strpar.inbregions_p
```

```
                sreg = num2str(icoreg);
                icovec = icoreg + (icosubsec 1)*strpar.inbregions_p;

                % labour
                strys.(['N_' ssubsec '_' sreg]) = strpar.(['phiN_' ssubsec '_' sreg '_p']) *
                    strpar.NT_p;

                % intermediate goods
                strys.(['Q_I_' ssubsec '_' sreg]) = sqrt(real(x_start_vec_2(icovec)).^2) *
                    strpar.(['phiY_' ssubsec '_' sreg '_p']) * strys.Y;

                % sub sectoral and regional expenditures
                strpar.(['phiQ_' ssubsec '_' sreg '_p']) = strys.P * strys.(['Q_I_' ssubsec '_
                    ' sreg]) + strpar.(['phiY_' ssubsec '_' sreg '_p']) * strys.Y * strys.P;

                % sub sectoral expenditures
                strpar.(['phiQ_' ssubsec '_p']) = strpar.(['phiQ_' ssubsec '_p']) + strpar.(['
                    phiQ_' ssubsec '_' sreg '_p']);

            end
            % aggregate total production
            strys.Q = strys.Q + strpar.(['phiQ_' ssubsec '_p']) / strys.P_D;

            % aggregate domestic total production
            strys.Q_D = strys.Q_D + strpar.(['phiQ_' ssubsec '_p']) * (1   strys.(['D_X_'
                ssubsec])) / strys.P_D;

            % sectoral expenditure share
            strpar.(['phiQA_' ssec '_p']) = strpar.(['phiQA_' ssec '_p']) + strpar.(['phiQ_'
                ssubsec '_p']) * (1   strys.(['D_X_' ssubsec]));

        end
    end
    for icosec = 1:strpar.inbsectors_p
        ssec = num2str(icosec);

        % sectoral price level
        strys.(['P_A_' ssec]) = strpar.(['omegaQA_' ssec '_p'])^(1/(strpar.etaQ_p   1)) * (
            strpar.(['phiQA_' ssec '_p'])/(strys.P_D * strys.Q_D))^(1/(1   strpar.etaQ_p)) *
            strys.P_D;

        % sectoral output
        strys.(['Q_A_' ssec]) = strpar.(['phiQA_' ssec '_p']) / strys.(['P_A_' ssec]);

        for icosubsec = strpar.(['substart_' ssec '_p']):strpar.(['subend_' ssec '_p'])
            ssubsec = num2str(icosubsec);

            % subsectoral price level
            strys.(['P_D_' ssubsec]) = strpar.(['omegaQ_' ssubsec '_p'])^(1/(strpar.(['etaQA_'
                 ssec '_p'])   1)) * (strpar.(['phiQ_' ssubsec '_p']) * (1   strys.(['D_X_'
                ssubsec]))/(strys.(['P_A_' ssec]) * strys.(['Q_A_' ssec])))^(1/(1   strpar.(['
                etaQA_' ssec '_p']))) * strys.(['P_A_' ssec]);

            % subsectoral output
            strys.(['Q_D_' ssubsec]) = strpar.(['phiQ_' ssubsec '_p']) * (1   strys.(['D_X_'
                ssubsec])) / strys.(['P_D_' ssubsec]);

            for icoreg = 1:strpar.inbregions_p
                sreg = num2str(icoreg);
                % subsectoral regional price level
                strys.(['P_D_' ssubsec '_' sreg]) = strpar.(['omegaQ_' ssubsec '_' sreg '_p'])
                    ^(1/(strpar.(['etaQ_' ssubsec '_p']) 1)) * (strpar.(['phiQ_' ssubsec '_'
                    sreg '_p'])/strpar.(['phiQ_' ssubsec '_p']))^(1/(1 strpar.(['etaQ_'
                    ssubsec '_p']))) * strys.(['P_D_' ssubsec]);

                % subsectoral output
                strys.(['Q_' ssubsec '_' sreg]) = strpar.(['phiQ_' ssubsec '_' sreg '_p']) /
                    strys.(['P_D_' ssubsec '_' sreg]);

                % subsectoral price level of primary production factors
                strys.(['P_' ssubsec '_' sreg]) = ((strys.(['P_D_' ssubsec '_' sreg])^(1
                    strpar.(['etaI_' ssubsec '_p']))   strpar.(['omegaQI_' ssubsec '_' sreg '
                    _p']) * strys.P^(1   strpar.(['etaI_' ssubsec '_p'])))/(1   strpar.(['
                    omegaQI_' ssubsec '_' sreg '_p'])))^(1/(1   strpar.(['etaI_' ssubsec '_p'
                    ])));

                % subsectoral gross vlaue added
                strys.(['Y_' ssubsec '_' sreg]) = strpar.(['phiY_' ssubsec '_' sreg '_p']) *
                    strys.Y * strys.P / strys.(['P_' ssubsec '_' sreg]);

                icovec = icoreg + (icosubsec 1)*strpar.inbregions_p;
                if strpar.(['etaNK_' ssubsec '_' sreg '_p']) ~= 1
                    % subsectoral regional capital stock
```

```
                    strys.(['K_' ssubsec '_' sreg]) = sqrt(real(x_start_vec_1(icovec)).^2) *
                        strys.(['Y_' ssubsec '_' sreg]);

                else
                    % subsectoral regional labour productivity
                    strys.(['A_N_' ssubsec '_' sreg]) = sqrt(real(x_start_vec_1(icovec)).^2);

                end

            end
        end
    end
    if strpar.phiG_p > 0
        % init government expenditure
        strys.G = x(end 1) * strys.Y;

    end
end
```

F Estimation of Elasticity of Substitution

Here we estimate the elasticity of substitution between different sub-sectors and sectors in one region. Therefore, we use the respective demand for each sector in each nest to estimate the following regression equation

$$ln\left(\frac{P^D_{s,t}}{P^D_{s,t-1}}\right) - log\left(\frac{P^D_{k,t}}{P^D_{k,t-1}}\right) = (1-\eta^{Q^A}_k)\left(log\left(\frac{P^D_{s,t}\,Q^D_{s,t}}{P^D_{s,t-1}\,Q^D_{s,t-1}}\right) - log\left(\frac{P^A_{k,t}\,Q^A_{k,t}}{P^A_{k,t-1}\,Q^A_{k,t-1}}\right)\right). \tag{166}$$

We approximate the domestic price levels with the price levels derived from the gross value added deflator for the respective sectors. We also need to approximate the change in nominal expenditures for domestic sectoral production with gross value added of the respective sector.

```
% ==========================================================
% ==== Estimation of elasticity of substitution between sectors ====
% ==========================================================

sFileName = [pwd() '\Data\Regression Data.xlsx'];
Real = readtable(sFileName, 'Sheet', 'Real');
Nom = readtable(sFileName, 'Sheet', 'Nominal');

% real GDP
BasicsReal = Real.A + Real.BDE;
ManConReal = Real.C + Real.F;
TransReal = Real.H;
ServReal   = Real.Services + Real.Health;
TotalReal = Real.Total;

% nominal GDP
BasicsNom = Nom.A + Nom.BDE;
ManConNom = Nom.C + Nom.F;
TransNom = Nom.H;
ServNom    = Nom.Services + Nom.Health;
TotalNom = Nom.Total;

% compute deflators
BasicsP = BasicsNom ./BasicsReal;
ManConP = ManConNom ./ManConReal;
ServP    = ServNom ./ ServReal;
AP = Nom.A./Real.A;
BDEP = Nom.BDE./Real.BDE;
CP = Nom.C./Real.C;
FP = Nom.F./Real.F;
SP = Nom.Services./Real.Services;
HealthP = Nom.Health./Real.Health;
TransP = Nom.H./Real.H;

P = TotalNom./TotalReal;
```

Health and Services

```
etaQ_p = 0.01;
X_vec = [diff(log(BasicsP./P)); diff(log(ManConP./P));...
diff(log(TransP./P)); diff(log(ServP./P))];
Y_vec = [diff(log(BasicsNom./TotalNom));diff(log(ManConNom./TotalNom));...
diff(log(TransNom./TotalNom)); diff(log(ServNom./TotalNom))];
fitlm(X_vec, Y_vec)
[pvaltest, Fvaltest, ~] = coefTest(fitlm(X_vec, Y_vec),[0 1], [1 etaQ_p]);

if pvaltest<0.05
disp('Reject H0')
else
disp('Do not reject H0')
end
```

Test whether the elasticity of substitution between Agriculture, Forestry, Aquaculture and Mining, Energy and Water supply is significantly different from 0.01. (maximum probability of type 1 error is 0.05)

```
etaQA_1_p = 0.01;
X_vec = [diff(log((AP./BasicsP))); diff(log(BDEP./BasicsP))];
Y_vec = [diff(log(Nom.A./BasicsNom));diff(log(Nom.BDE./BasicsNom))];
fitlm(X_vec, Y_vec)
[pvaltest, Fvaltest, ~] = coefTest(fitlm(X_vec, Y_vec),[0 1],...
[1 etaQA_1_p]);

if pvaltest<0.05
disp('Reject H0')
```

```
else
disp('Do not reject H0')
end
```

Test whether the elasticity of substitution between Manufacturing and Construction is significantly different from 0.01. (maximum probability of type 1 error is 0.05)

```
etaQA_2_p = 0.01;
X_vec = [diff(log((CP./ManConP))); diff(log(FP./ManConP))];
Y_vec = [diff(log(Nom.C./ManConNom));diff(log(Nom.F./ManConNom))];
fitlm(X_vec, Y_vec)
[pvaltest, Fvaltest, ~] = coefTest(fitlm(X_vec, Y_vec),[0 1],...
[1 etaQA_2_p]);

if pvaltest <0.05
disp('Reject H0')
else
disp('Do not reject H0')
end
```

Test whether the elasticity of substitution between Health and other Services is significantly different from 0.01. (maximum probability of type 1 error is 0.05)

```
etaQA_3_p = 0.01;
X_vec = [diff(log((SP./ServP))); diff(log((HealthP./ServP)));...
diff(log((TransP./ServP)))];
Y_vec = [diff(log(Nom.Services./ServNom));diff(log(Nom.Health./ServNom));...
diff(log(Nom.H./ServNom))];
fitlm(X_vec, Y_vec)
[pvaltest, Fvaltest, ~] = coefTest(fitlm(X_vec, Y_vec),[0 1],...
[1   etaQA_3_p]);

if pvaltest <0.05
disp('Reject H0')
else
disp('Do not reject H0')
end
```

Table 28: Endogenous Variables

Variable	LaTeX	Description	Unit/Formula
K	K	capital stock	currency
N	N	national hours worked	hours worked per total hours budget
SL	SL	sea level	mm
tas_1	tas_r	average surface temperature	°C
SfcWind_1	$SfcWind_r$	surface wind speed	$\frac{m}{s}$
pr_1	pr_r	precipitation	mm
sunshine_1	$sunshine_r$	sunshine	hours
hurs_1	$hurs_r$	relative surface humidity	percent
heatwave_1	$heatwave_r$	heatwave	number
maxdrydays_1	$maxdrydays_r$	maximum dry days	number
maxwetdays_1	$maxwetdays_r$	maximum wet days	number
storms_1	$storms_r$	share of persons affected by storms	percent
floods_1	$floods_r$	floods	number
fire_1	$fire_r$	fire	number
landslide_1	$landslide_r$	distribution of landslides	percentiles
I_1	I_k	sector private investment	quantity
Y_1	Y_s	sector GDP	quantity
Q_D_1	Q^D_s	domestically used sector output	quantity
Q_I_1	Q^I_s	sector intermediate inputs	quantity
M_1	M_s	sector imports	quantity
X_1	X_s	sector exports	quantity
D_X_1	D^X_s	world demand for sector exports	quantity
K_1	K_s	sector capital	quantity
N_1	N_s	sector employment	share of hours worked
P_D_1	P^D_s	domestic sector price	currency per quantity
P_M_1	P^M_s	imports sector price	currency per quantity
W_1	W_s	sector wage	currency per share of hours worked
Q_1_1	$Q_{s,r}$	regional sector output	quantity
W_1_1	$W_{s,r}$	regional wage rate for sector labour	currency per quantity
gA_1_1	$g^A_{s,r}$	regional growth rate of sector TFP	percent
tauKF_1_1	$\tau^K_{s,r}$	regional sector corporate tax rate on capital	percent
tauNF_1_1	$\tau^N_{s,r}$	regional sector labour tax rate on capital	percent
P_D_1_1	$P_{s,r}$	regional sector price level	currency per quantity
P	P	price level	index
lambda	λ	budget constraint Lagrange multiplier	utility units
P_D	P^D	domestic price level	currency per quantity
P_M	P^M	foreign price level	currency per quantity
C	C	consumption	quantity
H	H	houses	100 km^2
IH	I^H	investment in houses	100 km^2
PH	P^H	price level for houses	currency per quantity
DH	D^H	damages to the housing stock	100 km^2
omegaH	ω^H	Lagrange multiplier for the law of motion of houses	utility units
PoP	Pop	population	100 million persons
B	B	international traded bonds	quantity
BG	B^G	government debt	quantity
NX	NX	net exports	quantity
rf	r^f	foreign interest rate	percent
G	G	government expenditure	quantity
tauC	τ^C	consumption tax	percent
tauH	τ^H	tax on housing	percent
tauNH	τ^N	labour tax	percent
tauKH	τ^K	capital tax	percent
KG	K^G	public good capital stock	quantity
I	I	private investment	quantity
Y	Y	GDP	quantity
Q_U	Q^U	domestic used output	quantity
Q_D	Q^D	domestic produced and used products	quantity
Q_I	Q^I	demand for intermediate products	quantity
Q	Q	total production	quantity
M	M	imports	quantity
X	X	exports	quantity
G_A_DH	G^{A,D^H}	adaptation government expenditure for housing	quantity
Q_A_1	Q^A_k	sector aggregate output	quantity
P_A_1	P^A_k	sector aggregate price level	currency per quantity
KH_1_1	$K_{k,r}$	regional sector capital	quantity

Table 28 – Continued

Variable	LaTeX	Description	Unit
r_1_1	$r_{k,r}$	regional rental rate for sector capital	percent
I_1_1	$I_{k,r}$	regional sector investment	quantity
omegaI_1_1	$\omega^I_{s,r}$	shadow value of regional private sector investment	utility units
Q_1	Q_s	sector output	quantity
D_1_1	$D_{s,r}$	regional sector damages	index
D_N_1_1	$D^N_{s,r}$	regional sector damages to labour productivity	index
D_K_1_1	$D^K_{s,r}$	regional sector destruction of capital stock	quantity
K_1_1	$K_{s,r}$	regional sector capital	quantity
G_A_1_1	$G^A_{s,r}$	regional sector adaptation government expenditure	quantity
K_A_1_1	$K^A_{s,r}$	regional sector adaptation capital stock	quantity
I_AP_1_1	$I^{A,P}_{s,r}$	regional sector adaptation private expenditure	quantity
K_AP_1_1	$K^{A,P}_{s,r}$	regional sector adaptation private capital stock	quantity
P_1_1	$P_{s,r}$	regional sector price index	currency per quantity
Y_1_1	$Y_{s,r}$	regional sector GDP	quantity
N_1_1	$N_{s,r}$	regional sector employment	share of hous worked
Q_I_1_1	$Q^I_{s,r}$	regional sector intermediate inputs	index
A_1_1	$A_{s,r}$	regional sector TFP	index
A_N_1_1	$A^N_{s,r}$	regional sector labour specific TFP	index
A_K_1_1	$A^K_{s,r}$	regional sector capital specific TFP	index

Table 29: Exogenous Variables

Variable	LaTeX	Description	Unit/Formula
exo_PoP	η_{Pop}	population as the absolute change to the base year	100 Million persons
g_Y_s_r	$g^Y_{s,r,t} = \frac{Y_{s,r,t}}{Y_{s,r,0}}$	the annual growth rate of sectoral and regional value-added	percent
g_N_s_r	$g^N_{s,r} = \frac{\frac{N_{s,r,t}}{N_t}}{\frac{N_{s,r,0}}{N_0}}$	the annual growth rate of employment share	percent
exo_tauC	η_{τ^C}	consumption tax change to base year	percentage point change
exo_tauH	η_{τ^H}	housing tax change change to base year	percentage point change
exo_tauNH	η_{τ^N}	labour income tax paid by households change to base year	percentage point change
exo_tauKH	η_{τ^K}	capital income tax paid by households change to base year	percentage point change
exo_H	η_H	housing area to population ratio change to base year	m^2
exo_DH	η_{D^H}	damage to housing stock change to base year	percentage as share of curre
exo_BG	η_{BG}	structural balance change to base year	currency
exo_rf	η_{rf}	world interest rate change to base year	percent
exo_P	η_P	price level $\eta^P_t = ln(P_t) - ln(P_0)$	unitless
exo_M	η_M	import shock change to base year	currency
exo_X_1	$\eta_{X,k}$	change in demand for sector exports	quantity
exo_1_1	$\eta_{A,s,r} = ln(\frac{A_{s,r,t}}{A_{s,r,0}})$	TFP	unitless
exo_N_1_1	$\eta_{A^N,s,r} = ln(\frac{A^N_{s,r,t}}{A^N_{s,r,0}})$	labour specific productivity	unitless
exo_K_1_1	$\eta_{A^K,s,r} = ln(\frac{A^K_{s,r,t}}{A^K_{s,r,0}})$	capital specific productivity	unitless
exo_D_1_1	$\eta_{D,s,r}$	damage induced by climate change for TFP	share of base year GDP
exo_D_N_1_1	$\eta_{D^N,s,r}$	damage induced by climate change for labour productivity	share of base year GDP
exo_D_K_1_1	$\eta_{D^K,s,r}$	damage induced by climate change for capital productivity	share of base year GDP
exo_tauKF_1_1	$\eta_{\tau^K,s,r}$	sector and region corporate tax rate change	percent
exo_tauNF_1_1	$\eta_{\tau^N,s,r}$	sector and region labour tax rate change	percent
exo_GA_1_1	$\eta_{G^{A,landslide},s,r}$	sector adaptation expenditure against landslide	share of base year GDP
exo_G_A_DH	$\eta_{G^{A,H}}$	sector adaptation expenditure for housing	share of base year GDP
exo_IAP_1_1	$\eta^{I^{A,P}}_{s,r}$	private sector adaptation expenditure	share of base year GDP
exo_SL	η_{SL}	sea level change to base year	mm
exo_tas_1	$\eta_{tas,r}$	regional average surface temperature change to base year	$°C$
exo_SfcWind_1	$\eta_{SfcWind,r}$	regional surface wind speed change to base year	$\frac{m}{s}$
exo_pr_1	$\eta_{pr,r}$	regional average precipitation change to base year	number
exo_sunshine_1	$\eta_{sunshine,r}$	regional sunshine change to base year	hours
exo_hurs_1	$\eta_{hurs,r}$	regional hurs change to base year	percent
exo_heatwave_1	$\eta_{heatwave,r}$	regional heatwave change to base year	number
exo_maxdrydays_1	$\eta_{maxdrydays,r}$	regional maximum dry days change to base year	number
exo_maxwetdays_1	$\eta_{maxwetdays,r}$	regional maximum wet days change to base year	number
exo_storms_1	$\eta_{storms,r}$	regional share of persons affected by storms change to base year	percentage points

Table 29 – Continued

Variable	LaTeX	Description	Unit
exo_floods_1	$\eta_{floods,r}$	regional floods change to base year	number
exo_fire_1	$\eta_{fire,r}$	regional fire change to base year	number
exo_landslide_1	$\eta_{landslide,r}$	regional landslide	percentile

Table 30: Parameters

Variable	LaTeX	Description
inbsectors_p	S^A	number of aggregate sectors
inbregions_p	R	number of regions
lEndogenousY_p	l^Y	logical indicator for endogenous or exogenous production
lCalibration_p	l^{Calib}	logical indicator whether model is calibrated or not
lNationalK_p	l^K	logical indicator whether national capital stock or not
substart_1_p	$substart\_1\_p$	substart_1_p
subend_1_p	$subend\_1\_p$	subend_1_p
omegaQA_1_p	$\omega_k^{Q^A}$	distribution parameter for aggregate output from one sector
etaQA_1_p	$\eta_k^{Q^A}$	elasticity of substitution between products from different subsectors in one sector
phiM_1_p	$\frac{M_{k,0}\,P^M_{k,0}}{P_0\,Q_0}$	share of sector imports on total output
phiX_1_p	$\frac{X_{k,0}\,P_{k,0}}{P_{k,0}\,Y_{k,0}}$	share of exports on gross value added
phiQI_1_p	$\frac{Q^I_{k,0}\,P_0}{P_{k,0}\,Q_{k,0}}$	share of intermediate inputs on total production
D_X_1_p	D_k^X	long-run demand for exports
P_M_1_p	P_k^M	long-run price of sector imports
omegaM_1_p	ω_k^M	distribution parameter for imports from one sector
omegaQ_1_p	ω_k^Q	distribution parameter for output from one sector
etaQ_1_p	η_k^C	elasticity of substitution between regional production
etaI_1_p	η_k^M	elasticity of substitution between value added and intermediate products
rhoA_1_1_p	$\rho_{s,r}^A$	persistence productivity shock
tauKF_1_1_p	$\tau_{s,r}^{K,F}$	region and sector-specific tax rate on capital paid by firms
tauNF_1_1_p	$\tau_{s,r}^{N,F}$	region and sector-specific tax rate on labour paid by firms
phiY_1_1_p	$\frac{P_{s,r,0}\,Y_{s,r,0}}{P_0\,Y_0}$	share of regional and sectoral output
phiY0_1_1_p	$\frac{P_{s,r,0}\,Y_{s,r,0}}{P_0\,Y_0}$	initial share of regional and sectoral output
phiN_1_1_p	$N_{s,r,0}$	long-run share of regional and sectoral employment
phiN0_1_1_p	$N_{s,r,0}$	initial share of regional and sectoral employment
phiW_1_1_p	$\frac{W_{s,r,0}\,N_{s,r,0}}{P_{s,r,0}\,Y_{s,r,0}}$	share of regional and sectoral employment
phiL_1_1_p	$\phi_{s,r}^L$	coefficient of disutility to work
omegaQ_1_1_p	$\omega_{s,r}^Q$	distribution parameter for regional production
omegaQI_1_1_p	$\omega_{s,r}^{Q^I}$	distribution parameter for intermediate products
alphaK_1_1_p	$\alpha_{s,r}^K$	distribution parameter capital share
alphaN_1_1_p	$\alpha_{s,r}^N$	distribution parameter labour share
etaNK_1_1_p	$\eta_{s,r}^{N,K}$	elasticity of substitution between labour and capital
A_1_1_p	$A_{s,r}$	sector long-run TFP
phiGA_1_1_p	$\phi_{s,r}^{G^A}$	coefficient of effectiveness of government expenditure
deltaKA_1_1_p	$\delta_{s,r}^{K^A}$	depreciation rate of adaptation capital stock against landslide
gY0_1_1_p	$\frac{Y_{2,s,r}}{Y_{1,s,r}}$	initial sector growth
gN0_1_1_p	$\frac{\frac{N_{2,s,r}}{N_2}}{\frac{N_{1,s,r}}{N_1}}$	initial sector labour growth
omegaA_1_1_p	$\omega_{s,r}^A$	exponent for productivity growth
A_N_1_1_p	$A_{s,r}^N$	sector labour specific TFP
A_K_1_1_p	$A_{s,r}^K$	sector capital specific TFP
beta_p	β	discount factor
omegaP_p	ω^P	share of rational agents
gamma_p	γ	preferences for housing in utility function
delta_p	δ	capital depreciation rate
deltaH_p	δ^H	housing depreciation rate
deltaKG_p	δ^{K^G}	public capital depreciation rate
phiG_p	ϕ^G	elasticity of TFP to public capital
sigmaL_p	σ^L	inverse Frisch elasticity
sigmaC_p	σ^C	intertemporal elasticity of substitution

Table 30 – Continued

Variable	LaTeX	Description
etaQ_p	η^Q	elasticity of substitution between sectoral production
etaM_p	η^M	elasticity of substitution between sectoral imports
etaF_p	η^F	elasticity of substitution between foreign and domestic products
omegaF_p	ω^F	distribution parameter between foreign and domestic products
phiB_p	ϕ^B	coefficient of foreign adjustment cost
phiK_p	ϕ_0^K	coefficient of investment adjustment cost
tauC_p	τ_0^C	consumption tax
tauH_p	τ_0^H	tax on housing
tauNH_p	$\tau_0^{N,H}$	labour tax
tauKH_p	$\tau_0^{K,H}$	capital tax
tas_1	$tas_{r,0}$	initial regional tas (° C)
SfcWind_1	$SfcWind_{r,0}$	initial regional SfcWind (m/s)
pr_1	$pr_{r,0}$	initial regional average precipitation (mm)
sunshine_1	$sunshine_{r,0}$	initial regional sunshine (hours)
hurs_1	$hurs_{r,0}$	initial regional hurs (percent)
heatwave_1	$heatwave_{r,0}$	initial regional heatwave (days)
maxdrydays_1	$maxdrydays_{r,0}$	initial regional max dry days (days))
maxwetdays_1	$maxwetdays_{r,0}$	initial regional max wet days (days)
storms_1	$storms_{r,0}$	initial regional share of persons affected by storms (percent)
floods_1	$floods_{r,0}$	initial regional floods (number)
fire_1	$fire_{r,0}$	initial regional fire (number)
landslide_1	$landslide_{r,0}$	initial regional landslide (percentile)
phiQDD_p	$\frac{Q_0^I\, P_0}{P_0\, Q_0}$	share of domestically used and produced on total production
phiM_p	$\frac{M_0\, P_0^M}{P_0\, Q_0}$	share of imports on total production
SL0_p	SL_0	initial SL
PoP0_p	Pop_0	initial population
H0_p	H_0	initial stocks of houses
PH0_p	P_0^H	initial price of houses
Y0_p	Y_0	initial output
NX0_p	NX_0	initial net export to value-added ratio
P0_p	P_0	initial price level
P0_M_p	P_0^M	initial price level
N0_p	N_0	initial employment
rf0_p	r_0^f	initial world interest rate
sH_p	$s_0^H = \frac{P^H I^H}{PY}$	share for housing investments

G How to use the model?

G.1 Usage

1. In order to use the model you need to install Dynare (at least version 4.6.1) and Matlab (at least 2020b) or Octave on your computing machine. For Octave, you need to have version 5.2.0 as reported by the Dynare team. Furthermore, MS Excel is used to specify the parameters and to save the results. Result tables are saved additionally in Latex format.
2. You need to download the repository from Github.
3. Open Octave or Matlab GUI and browse to the location of the folder in your computer. You have the right folder if the command `pwd()` returns `YourPath/DGE-CRED/DGE_CRED_Model`.
4. The script `RunSimulations.m` has to be executed in order to run simulations for different scenarios. Make sure that the scenarios and model parameters are defined in the file `ModelSimulationandCalibrationKSectorsandRRegions.xlsx`. You need to adopt the number of sectors and regions in the file `DGE_CRED_Model.mod`. All program files are described in the next section.
5. The simulation results are stored in the file `ResultsScenariosKSectorsandRRegions.xlsx`.

G.2 Folder structure

1. The main file containing all necessary mod-files is `DGE_CRED_Model.mod`. This file includes the following files stored in the `ModFiles` folder:
   (a) `DGE_CRED_Model_Declarations.mod` declares all endogenous and exogenous variables of the model and structural parameters.
   (b) `DGE_CRED_Model_Parameters.mod` assigns values to the structural parameters of the model.
   (c) `DGE_CRED_Model_Equations.mod` contains the equations of the model.
   (d) `DGE_CRED_Model_LatexOutput.mod` produces latex output for documentation of the declared variables and model equations.
2. Subroutines responsible for finding the initial and terminal conditions are located in the subfolder `Functions`:
   (a) `Simulation.m` simulates the model
   (b) `SteadyState.m` script responsible to calibrate the model
   (c) `Miscellaneous` folder containing different scripts and routines not necessary to run the model.
   (d) `Auxiliary` folder containing different scripts necessary to run the model.
3. To define scenarios and structural parameters you need to create an Excel file located in the subfolder `ExcelFiles`:
   (a) `ModelSimulationandCalibrationforKSectorsandRregions.xlsx` has multiple sheets:
      i. data for calibration `Data`
      ii. initial `Start`
      iii. structural parameters of the model `Structural Parameters`
      iv. coefficients for regional and sector-specific damage functions `Climate Damage Functions (Labour, Capital, TFP)`
      v. `Baseline` scenario and other optional scenario sheets `Adaptation and Extremes` defining paths for exogenous variables
      vi. `Data` to load external data sources
   (b) `ResultsScenariosKSectorsandRregions.xlsx` has as many sheets as scenarios defined in the previous Excel file.
4. The latex files produced by `DGE_CRED_Model_LatexOutput.mod` are stored in the sub-folder `LatexFiles`:
   (a) the system of dynamic equations as implemented in Matlab `DGE_CRED_Model_Dynamic`, `DGE_CRED_Model_Dynamic_content`
   (b) names of endogenous, exogenous variables and parameters `DGE_CRED_Model_latex_definitions`
   (c) the system of dynamic equations in original form without auxiliary variables for leads and lags `DGE_CRED_Model_original`, `DGE_CRED_Model_original_content`
5. The file to run different simulations is `RunSimulations.m`.
6. A Matlab function to find solutions to the static system of equations is `DGE_CRED_Model_steady_state.m`.