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Economic Consequences of Climate-Induced Changes in Crop Yields in a Water-Abundant Region*

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Abstract: A concerning consequence of climate change is the impact that reduced rainfall and increased temperatures are predicted to have on agricultural yields, with subsequent economic impacts across regions based on their reliance on agricultural production and knock-on effects through impacts on prices and trade. Several studies have used the relationship between climate variables and agricultural yields to project changes in agricultural productivity under climate scenarios as the input to Computable General Equilibrium models, however such studies are typically dominated by water-scarce countries. We extend this by considering the differential regional impacts and economic consequences within a water-abundant nation, permitting the analysis of climate-induced impacts on regional trade and production and consumption links between regions. Our framework estimates the historical relationship between climate variables and agricultural yields for four crop types (wheat, oats, winter barley and spring barley), calculates the future productivity of land under two climate scenarios, and then simulates the economy-wide impacts of these in a two-region computable equilibrium model of Western and Eastern Scotland. Our results suggest that there could be negative impacts of future changes in climate agricultural yields, with an overall reduction productivity by the end of the century which depends on climate scenarios. While the largest (absolute) negative economic impacts are in Eastern Scotland region, where cereal production is concentrated, impacts transmit through trade between the two regions, showing that policies to improve adaptation to climate change within the Agricultural sector would help to minimise overall economic losses across even water-abundant regions.
Keywords: agricultural yields; climate projections; computable general equilibrium; regional economic impacts; Scotland
JEL Codes: D58, Q54, R11, R13, R15

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1. INTRODUCTION

Rising temperatures, changes in the pattern of rainfall, and increasingly frequent weather extremes are impacting on agricultural production (IPCC, 2022). Such impacts are particularly being felt in already dry areas, while climate scenarios also predict increasing heterogeneity across the globe. As well as significant impacts on food security and agricultural production, these will drive significant economic consequences. The frontier of research linking environmental change with economic consequences is a critical area for truly interdisciplinary research (Rising et al., 2022).

Research into the relationship between climate and economy has developed in a number of areas. There is a rapidly expanding academic literature on the links between climate variables and economic activity, including the impact of temperature on labour productivity (Burke et al., 2015) and how this might differ by industrial sector (e.g., Schleypen et al., 2022). Increasing temperatures have also been associated with greater incidences of suicides (Gao et al., 2019), higher rates of crime (Ranson, 2014) and impacts on mental health (Charlson et al., 2022). Additionally, studies have examined the role of climate on agricultural production.[1] Burke and Emerick (2016) find that corn yields could be 15% lower across the US by 2050. Degife et al. (2021) project reductions in maize yields under most future Representative Concentration Pathways (RCPs)[2] in Ethiopia. Zhang et al. (2017) find that future crop yields in China could all be lower than their current values.[3] Examining wheat yields in three regions of the UK, Slater et al. (2022) identify increasing variability of wheat yields in the last decade, a negative association between extremes of rainfall during summer with yields, and that the (positive) impacts of projected higher temperatures on yields might be offset (negatively) by increased rainfall and rainfall variability.[4]

While there is growing evidence on the negative relationship between future climate pathways and agricultural output, the consequences on overall economic change at the regional level is less well studied. Changes in the environment will be region-specific and fundamentally affect on regional economic outcomes. Alongside policies to address climate change mitigation and adaptation responses being national as well as regional, this suggests a fundamental role for regional analysis in helping policymakers in economic planning (Court and Erfanian, 2019).

The myriad ways in which changes in climate might lead to regional economic impacts has led to a growing use of empirical modelling, in particular Computable General Equilibrium (CGE) models. These frameworks are multisectoral by design, and so able to connect changes in the agricultural sector to the rest of the economy. They are also able to incorporate

[1] For early important contributions see Deschênes and Greenstone (2007); Schlenker and Roberts (2009); Lobell et al. (2011).

[2] Although not focused on the long-term relationship between agricultural output and climate, Amare et al. (2018) show that rainfall "shocks" – defined as period with rainfall more than one standard deviation above or below the long-term mean values - also have impacts on agricultural productivity.

[3] Zhang et al. (2017) also include humidity, wind, sunlight, and evaporation and find that point estimates are impacted by the range of climate variables included.

[4] Studies which have examined farmers adaptation to changing climates in the long run using a Ricardian approach include Mendelsohn et al. (1994) however to our knowledge the relevant data on agricultural land prices covering the full UK is not available.

response of agents in production and consumption to the consequences which could follow from disturbances to the economy by making assumptions about agents' price sensitivity behaviour. Whilst these assumptions may be seen as restrictive and could constitute a limitation to the methodology, they allow researchers to employ a tractable and controlled framework so that likely ex ante consequences of changes in productivity can be examined. CGE studies however have, to date, typically had a focus on areas where agriculture is a critical industry, and on resource-scarce countries. Robinson et al. (2012) - in an early application of what has become a widely used method - link a climate model to econometric estimates of the relationships between climate variables and agricultural yields to project future agricultural productivity for Ethiopia.[5] Further cases examining Ethiopia include Gebreegziabher et al. (2016); Borgomeo et al. (2018); Solomon et al. (2021) who project that the output of key crops will fall by 2050 by between 12 and 30% causing higher prices, reducing incomes and (domestic and external) consumption and reducing economic activity by up to 31%. In a recent (regional) analysis for Brazil, Souza and Haddad (2021) examine regional impacts of changes in crop yields, finding impacts of between 0.4% and 1.8% of GDP.

Our contribution in this paper is three-fold. First, most studies of future changes in climate have focused on resource-scarce countries, so our analysis of a water-abundant region, Scotland, is novel. Second, much of the analyses to date uses changes in crop yields as proxies for the changes in agricultural productivity which could result in future scenarios. Our analysis features a particular treatment of natural capital within the factors of production open to agricultural sectors, permitting us to explicitly introduce future changes in agricultural productivity directly as changes in the productivity of this resource.[6] Third, we have an illustrative spatial dimension to the CGE model where we distinguish between Western and Eastern Scotland. This lets us undertake a within-country analysis, and so capture the indirect and induced intra-country impacts of changes in each region, as well as differences in the direct changes in each region reflecting regional land use and projected productivity changes.

We proceed as follows. Section 2 sets out the context for crop production in Scotland, describing current activities and their spatial distribution across Scotland, and future climate projections for regions of Scotland. Section 3 then describes our econometric estimation of the historical relationship between climate variables and crop yields over time. Our CGE model is set out in Section 4. The climate projections and econometric results provide us with the information necessary to introduce projections of changes in land productivity by region into our CGE model, and we show our results in Section 5, including sensitivity to different specifications, including alternative climate projections, and introducing the

[5] The method by Robinson et al. (2012) also considers direct shocks to the Ethiopian economy from a range of other routes in addition to crop and livestock, including hydrological impacts, energy production, and infrastructure.

[6] Our approach is most similar to Souza and Haddad (2021) in that region-specific crop yields are projected based on an econometrically estimated relationship for previous relationships which are then projected forwards under climate scenarios and used as the input to a CGE modelling framework. Unlike Souza and Haddad (2021) we treat projected productivity changes as applying only to natural capital, rather than the productivity of the agricultural sector, and we also model natural capital (land) as a fixed factor of production.

productivity disturbance separately in each region to identify the transmission mechanisms of our regional results. Section 6 discusses our findings and provides conclusions.

2. SCOTTISH AGRICULTURAL PRODUCTION, YIELDS AND CLIMATE PROJECTIONS

Agriculture activities – including crop production - make a significant contribution to the Scottish economy. Total farm incomes in 2021 were £2.6 billion (Scottish Government, 2022), while farms in Scotland classified as "Specialist cereals", "General cropping" and "Specialist horticulture and permanent crops" earning £914 million (34% of total farming income) in that year.[7] There is over 5.6 million hectares of agricultural land in Scotland (Scottish Government, 2021). By area, the vast majority (over 98%) of Scotland's cereals are in four main crops: Wheat, Spring Barley, Winter Barley and Oats. Of these four crops, Scottish cereal production in 2021 constituted 890 thousand tonnes of wheat, 333 thousand tonnes of winter barley, 1451 thousand tonnes of spring barley, and 189 thousand tonnes of oats.[8] The UK is largely self-sufficient in crop production, with barley and oats production exceeding consumption and 81% of the UK's wheat consumption coming from domestic production. Much of the UK's crops are used in animal feed, and so underpin the significant non-crop activities of the farming sector, with an important share of wheat and oats production milled for use in food products as well as a significant portion of the UK's barley production used in brewing and distillation (DEFRA, 2022).

Agricultural activities are not evenly distributed across Scotland, reflecting the countries topological, soil and climate characteristics. The Land Capability for Agriculture (LCA) system notes that the land area most suitable for Arable Agriculture (LCA classes 1-3.1) is primarily located in the Eastern of the country, with the land capable for Rough Grazing largely in the steeper, Western parts of the country (James Hutton Institute, 2022). In total, 62% of agricultural land is in the Western areas of the country, however this is predominantly comprised of grass and rough grazing, with the vast majority of the land used for crop production (86%) located in Eastern areas.[9]

Cereal yields – tonnes of production per hectare of land used - provide a useful measure for the productivity of agricultural land. From the historical records on wheat production, Slater et al. (2022) notes that wheat yields increased significantly between the 1950s and 1990s but have plateaued in recent years. Data on barley and oats yields became available in 1948 and 1980 respectively and show a similar but not as rapid increase. Data on cereal production for regions and nations within the UK is currently available from 1999 (DEFRA, 2022), which shows long term increases in crop yields as well as increases in crop yield

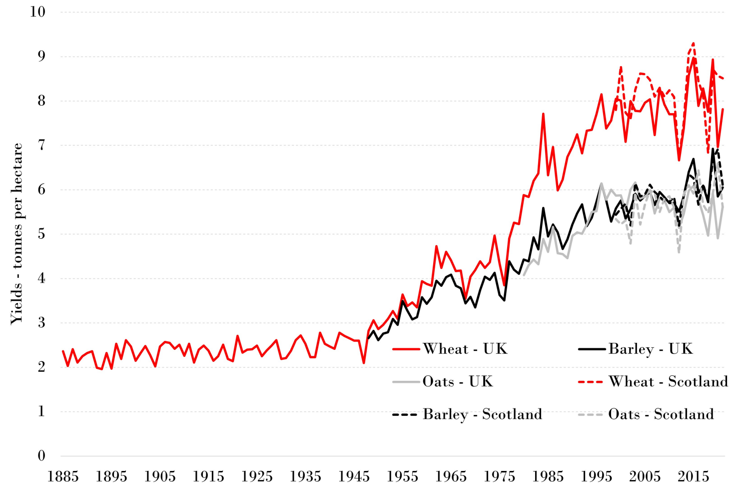
[7]In 2021, Scotland had 1.7 million cattle, 6.8 million sheep, 341,000 pigs and 14 million poultry (Scottish Government, 2021). The major non-crop farm types with significant revenues include "Cattle and sheep" (£705 million), "Mixed holdings" (£336 million) and "Specialist dairy" (£321 million).

[8]Spring Barley is generally sown in March and harvest in Autumn, with Winter Barley planted in the preceding September. Wheat and Oats are both harvested in September with the majority of wheat in Scotland sown in the winter, with Oats sown in the spring (Scottish Government, 2022).

[9]We have classified the following areas as Western Scotland – Na h-Eileanan Siar, Highland, Argyll and Bute, Clyde Valley, Ayrshire and Dumfries and Galloway – while Eastern Scotland is classified as East Central, Lothian, Fife, Tayside, Grampian and the island regions of Orkney and Shetland.

Figure 1:

Key cereals yields for the UK and Scotland
for wheat, oats and barley, 1885 to 2021



Source: DEFRA (2022)

variability at UK as well as Scotland level (Figure 1).

Crop production is dependent on weather and climate conditions. The UK government has noted that water stress is impacting on long-term wheat yields in southern parts of the UK, as well as weather extremes at crucial times in crop growing seasons impacting on production (DEFRA, 2022). Broadly put, the UK has become warmer and wetter when compared to long term averages. Temperatures in the last decade were around 1° warmer than the last fifty years of the nineteenth century, while average winter and summer rainfall was 12% and 13% higher than the 1960-1990 average. Significant changes in rainfall extremes are particularly evidenced in Scotland, where rainfall on days with heavy rain was up by 17% in the last decade (Met Office, 2018).

Eastern and Western Scotland are projected to see temperature and rainfall changes continuing over the next century relative to their recent (i.e. 1982-2000) averages (Met Office, 2018).[10] Under RCP2.6, both regions of Scotland are projected to see increases in summer and winter temperatures relative to the 1981-2000 average by the end of the century. The mid-point of the winter temperature increase is slightly higher in the Western (1°) than Eastern (0.9°) area. Projections of rainfall on the other hand behave differently in each season, with increasing winter rainfall in both Western Scotland (up 11%) and Eastern Scotland (up 9%). Summer rainfall is projected to be lower than the previous average, with 50th percentile projections of drier summers of 11% and 10% respectively in West and East

[10]Projections for the UK under low, medium and high emissions scenarios to 2100 are provided publicly broken down across 12 administrative UK regions, and comprise mean annual, summer and winter temperature changes (in degrees C), as well as summer and winter rainfall changes (as %s) relative to their 1981-2000 averages (Met Office, 2023). These are also provided for watersheds however this is below the level at which we have crop production data. As well as showing the prediction for each variable at the 50th percentile (the solid line in each panel) we also show the range around this projection, at the 5th, 10th, 90th and 95th percentile to show the uncertainty surrounding each projected value.

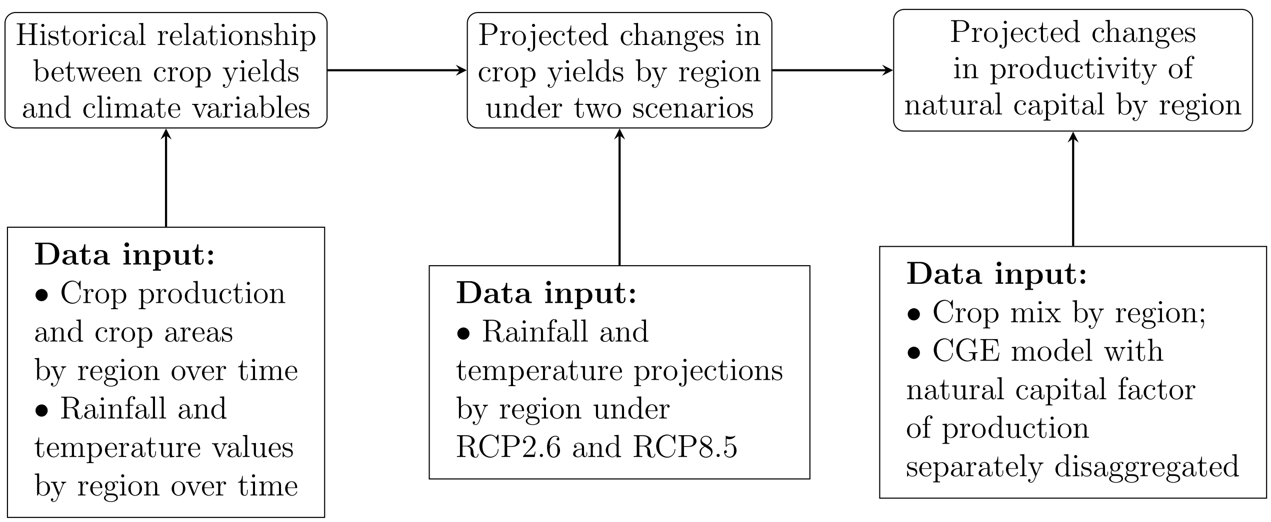
of the country.

3. METHOD

3.1. Overview of approach

As set out in Section 1, we are interested in quantifying the economic impacts on Eastern and Western Scotland of projected climate-related changes via changes in the productivity of natural capital (land). Our three step-procedure is set out in Figure 2, while the steps in each element are set out in Sections 3.2 and 3.3. The calculated changes in productivity of natural capital are introduced as disturbances to the CGE model, the details of which are set out in Section 4.

Figure 2: Three-step method from historical relationships to CGE simulation



3.2. Econometric analysis of the impact of climate variables on crop yields

3.2.1. Method and data

Naturally, we wish to use the most detailed and appropriate data with a broad coverage of regions, crop types, as well as granularity over time for both our crop and climate variables. There is a long time series for some crop yields for the UK as a whole, with data available for a shorter time period for other crops and with more geographic detail within the UK. For instance, Scottish Government (2021) contains detail on crop types, production area and across geographies, but only provides annual figures covering five years (2017 to 2021). DEFRA (2022) provide similar levels of cereal production as Scottish Government (2021) but do not provide details of production by crop by region within Scotland, producing figures for 11 UK regions between 1999 and 2021. Again, a significant limitation is the granularity across time periods, with only annual data available on crop production for the UK and sub-regions. This stands in contrast to the sub-regional temperature variables which are available from the Met Office for temperature and rainfall data by month from 1884 and 1836 respectively (Met Office, 2023). We do however find some restrictions on the spatial granularity with public data available for nine "climate districts" within the UK, of which three are in Scotland.[11]

Our econometric analysis thus uses yields (tonnes per hectare) for nine regions (DEFRA, 2022), aligned with a consistent set of temperature, rainfall and sunshine data to produce a set of consistent measures of both over the longest period of analysis possible with UK-specific data (Met Office, 2023). We therefore aggregate the 11 UK regions on which crop data is published into nine which are consistent with climate districts, giving us annual yield figures for each crop type by region covering the period between 2000 and 2021 (inclusive).[12] *Appendix A* provides the mapping between crop and climate regions.

With our data we can estimate the relationship between agricultural yields by crop, rainfall, temperature and sunshine as our climate variables and our set of region and time specific values. Formally, we estimate the relationship as:

$$y_{vitm} = \sum_{s=A,Sp}^{s=W,Su} \gamma_s \big(\mathbb{1}(s) \times Rain_{itm}\big) + \sum_{s=A,Sp}^{s=W,Su} \delta_s \big(\mathbb{1}(s) \times Temp_{itm}\big) + \tau' X_{itm} + \alpha_{im} + \lambda_{tm} + \theta_i \cdot t + \varepsilon_{vitm} \quad (1)$$

In equation 1, y_{vitm} is the yield for crop v (production per hectare) in region i in year t and month m. We use monthly values for $Rain$ and $Temp$, respectively, total precipitation (in millimetres) and temperature (average daily mean temperature). Rain and Temp also include the square of the values to test for the non-linear relationship between yields and our climate variables.

We take the growing season as months following after the harvest in Autumn so that monthly values relate to those from September onwards (i.e. September in year $t-1$ through to August in year t) are the relevant climate variables for the yield of crop v in year t. We do not separately report the coefficients on individual months, but group across summer and winter periods of the growing season so that these effects can be related to the projections of future changes in winter and summer rainfall and temperature.[13] $\mathbb{1}(s)$ is an indicator variable for summer and winter. The omitted seasons are Autumn and Spring. X_{itm} additionally control for the interaction of $Summer$ and $Winter$ with Sun, the duration of bright sunshine (in hours) and its square, as before, and the levels and squares of $Rain$, $Temp$, and Sun.

We include region-month-specific fixed effects (α_{im}) that control for the geographic location, soil type and soil quality and region-specific time invariant characteristics. We include

[11] Met Office weather variables (incl. temperature and rainfall by month) by regions (Scotland, NI, Wales and N and S England) and (nine) climate districts (N Scotland, E Scotland, W Scotland, Midlands, NW England and N Wales, E England and North East, East Anglia, SE and Central England and SW England and S Wales).

[12] Note (Table A1) that crop data on East and West Midlands is merged into a single region, which is consistent with the "Midlands" definition of climate variables, while "Yorkshire and the Humberside" and "North East" are also merged to be consistent with the Met Office identification of "North East".

[13] Our results are also robust when using individual Summer and Winter months interactions instead of pooling them together (Appendix table B1).

year-month-specific fixed effects (λ_{tm}) that control for annual shocks and national policies in each year as well as seasonality (Zhang et al., 2017). Finally, we also control for region-specific time trends ($\theta_i.t$).[14] All values are in logs, so that the elasticities can be interpreted as percentages.

In our core specification, we cluster standard errors at the Region level.[15] To test for spillover effects between regions (Baylis et al., 2011), we also show that our results are robust to allowing for spatial correlation in the distance dimension by using Conley standard errors (Conley, 1999). Appendix table B3 presents Conley Standard errors for our core results using a distance cutoff of 500 Km.[16] This approach allows correlation between the error terms of two observations up to this cutoff beyond which the correlation is assumed to be zero. Because this approach treats spatial dependencies as noise, it may potentially overlook structural spillover effects. However, our identification strategy includes Region FEs $\times$ Month FEs and Region FEs $\times$ Year trends, exploiting only within region-month variation. Therefore, it already inherently partially accounts for common correlated effects, and structural cross-sectional dependency does not materially affect the interpretation of our results (Pesaran, 2006; Baltagi, 2021). Indeed, Conley standard errors are statistically indifferent from standard errors clustered at the regional level.[17]

3.2.2. Results from econometric analysis

Table 1 shows the econometric results from our core specification. We find that winter rainfall is particularly damaging to crop yields, with each 1% increase in precipitation in winter reducing crop yields by around 0.20%. The impact is slightly higher for oats (-0.21%) than winter barley (-0.18%). That this effect is non-linear is supported by the significance for all four crops of the quadratic term, so that larger increases in winter rainfall are consistent with greater reductions in yields. While summer rainfall seems to be damaging for wheat (-0.09%) and winter barley (-0.14%). Meanwhile winter temperature has adverse effects only on wheat (-0.14%).

[14] Please note that we do not separately observe coefficients for seasons, as they are captured by monthly fixed-effect interactions.

[15] While we remain conservative and use aggregate clusters to avoid bias, this might lead to having too few clusters. In Appendix table B2, we also show our results are robust to clustering standard errors at the Region-Year level.

[16] Results are also robust to alternative distance cutoffs of 100 km and 1000 km.

[17] While these results reinforce the validity of our main results, we refrain from interpreting them in depth due to their inherent limitations of structural dependencies in further dimensions and the use of regional centroids, which may constrain precision of these standard errors.

Table 1: Effect of rain and temperature on crop yield

	Dependent variable is log yields of			
	Wheat	Oats	Winter Barley	Spring Barley
	(1)	(2)	(3)	(4)
Winter × log(Rain)	-0.21	-0.21	-0.19	-0.21
	(0.06)***	(0.09)*	(0.04)***	(0.05)***
Summer × log(Rain)	-0.09	0.05	-0.14	-0.06
	(0.04)*	(0.04)	(0.02)***	(0.03)
Winter × log(Temp)	-0.14	0.11	-0.04	0.06
	(0.03)***	(0.06)	(0.07)	(0.08)
Summer × log(Temp)	-1.19	2.20	-1.86	1.14
	(0.67)	(1.31)	(1.93)	(1.85)
Winter × $(\log(\text{Rain}))^2$	0.02	0.02	0.02	0.02
	(0.01)***	(0.01)*	(0.01)***	(0.01)***
Summer × $(\log(\text{Rain}))^2$	0.01	-0.01	0.02	0.01
	(0.01)	(0.01)	(0.00)***	(0.00)*
Winter × $(\log(\text{Temp}))^2$	0.04	0.03	0.02	0.02
	(0.02)*	(0.04)	(0.03)	(0.04)
Summer × $(\log(\text{Temp}))^2$	0.24	-0.43	0.36	-0.21
	(0.12)*	(0.25)	(0.33)	(0.34)
log(Rain, Temp, Sun)	✓	✓	✓	✓
$(\log(\text{Rain, Temp, Sun}))^2$	✓	✓	✓	✓
Season FEs × log(Sun)	✓	✓	✓	✓
Season FEs × $(\log(\text{Sun}))^2$	✓	✓	✓	✓
Region FEs × Month FEs	✓	✓	✓	✓
Year FEs × Month FEs	✓	✓	✓	✓
Region FEs × Year trend	✓	✓	✓	✓
Region	9	9	9	9
N	2369	2369	2369	2369
Mean dependent variable	2.01	1.71	1.86	1.65
Base period	Aut/Spr	Aut/Spr	Aut/Spr	Aut/Spr
Included years	2000-2021	2000-2021	2000-2021	2000-2021
R^2	0.85	0.63	0.79	0.75
Adjusted R^2	0.82	0.55	0.75	0.71

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors are in parentheses and allow for clustering of the model error at the Region level. The dependent variable is the log of Wheat Yield in column (1), Oat Yield in column (2), Winter Barley Yield in column (3), and Spring Barley Yield in column (4). The Winter period of growing season includes December, January, and February. Summer includes June, July, and August. Spring and Autumn are omitted; hence, our effects are relative to these seasons. Rain is defined as the total precipitation per month in millimetres and Temp, the average of daily mean temperatures over the month in degrees Celsius. The regression also controls for the interaction of seasons with the log(Sun) and $(\log(\text{Sun}))$,[2] the duration of bright sunshine during the month in hours. Further, levels of Rain, Temp, Sun, and their squares are included in the regression, but their point estimates are not shown. The unit of observation is region-year-month.

3.3. Projecting changes in crop yields and changes in natural capital productivity

With the relationships between crop yields and climate variables now estimated, we can use the climate projections for each region of Scotland to calculate changes in future crop yields by region. We use the projected changes in summer and winter rainfall and temperature in the last two decades of the 21st century (i.e., 2080-2099) relative to 1980-2000 and multiply these by our estimated coefficients shown in Table 1. Two climate scenarios are used from Met Office (2018), specifically RCP2.6 and RCP8.5.

The change in total crop yields for each region are thus the estimated changes in yields for each crop multiplied by that crops share in each region of Scotland. Changes in total crop yields by each region are thus impacted by the projected percentage changes of the climate variables for each region and the relative shares of each crop in each region.

Table 2 shows the changes in projected yields by each crop and region and the overall change in crop yields by region between 1980-2000 and the last two decades of the current century (2080-2099). Panel (a) and (b) show our projections for Western and Eastern Scotland respectively. The final row in each panel shows the total change in crop yields in each region, which are negative in each case, reflecting lower yields under these climate projections. In aggregate, we have larger (i.e. more negative) changes in crop yields in Western Scotland in each scenario, with changes in all crops more negative in this region compared to Eastern Scotland.

Table 2: Changes in crop yields by scenario and region, 2080-2099 compared to 1980-2000

	Western Scotland	**Eastern Scotland**
Panel A: Scenario RCP2.6		
Wheat	-5.57%	-6.59%
Oats	-2.31%	-1.89%
Winter Barley	-0.55%	-0.31%
Spring Barley	-2.31%	-1.89%
Total	-2.90%	-2.89%
Panel B: Scenario RCP8.5		
Wheat	-16.81%	-18.95%
Oats	-6.30%	-5.04%
Winter Barley	-2.20%	-1.06%
Spring Barley	-6.30%	-5.04%
Total	-8.37%	-8.06%

Source: Authors calculations.

4. MACRO-MODELLING FRAMEWORK AND STRATEGY

4.1. Computable General Equilibrium model

To simulate the economy wide impact of changes in agricultural productivity we develop and apply a two-region dynamic computable general equilibrium (CGE) model of Western and Eastern Scotland. The model combines features of a standard multiregional CGE model (see for instance Figus et al., 2018) but augmented to incorporate natural capital in the production of agriculture output (Allan et al., 2018).[18] The model is calibrated on a two-region Input Output (IO) table for Scotland in which data from the 2017 IO table for Scotland produced by the Scottish Government (Scottish Government, 2023) is combined with information on interregional trade from Thissen et al. (2019). Details on how we disaggregate natural capital and allocate to West and East Scotland are given in Appendix D.

The production structure of 10 productive industries[19] is represented using conventional production functions where capital and labour Details about the sectoral aggregation is provided in Appendix C.are combined with intermediate to produce gross output. For agriculture (sector A), natural capital is added as factor of production as follows:

$$Y_{At} = \left(\alpha K_{At}^{\rho} + \beta L_{At}^{\rho} + A^{NK} \gamma NK_{At}^{\rho}\right)^{\frac{1}{\rho}} \tag{2}$$

In equation 2, Y, K, L and NK are value added, capital, labour and natural capital (land) respectively, α, β and $\gamma \in (0,1)$ are share parameters, A^{NK} is a productivity parameter for natural capital, and ρ is an elasticity parameter. Capital stocks can accumulate over time through investment following Lecca et al. (2013) (Equations E.51-E.54), labour is supplied as a semi fixed factor (Equations E.55-E.56) in that the working population is fixed but there is a pool of unemployed labour in each of the two regions where the unemployment rate is inversely related to the real wage (Equation E.11) (Blanchflower and Oswald, 1995). However, crucially, land is a fixed factor of production (Equation E.57).

Firms and households use and consume a mix of imported and domestically produced goods following a standard Armington (1969) assumption (Equations E.21-E.27 for intermediate and export, E.39-E.42 for households, E.47-E.50 for investment goods). The two Scottish regions can trade either with the rest of the world (which includes the rest of the UK) and with the other Scottish region. Whilst rest of the world is exogenous to the model hence the import price is fixed (Equation E.1), each region exports to the other Scottish region (Equation E.26) at their output price which (Equation E.2) is determined endogenously in the model and is the result of firms' cost minimization including the costs of all factors of production.

[18]The full model listing is provided in Appendix E. In what follows, we reference the equations from Appendix E in the main body by indicating the equation number preceded by the letter E.

[19]Details about the sectoral aggregation is provided in Appendix C.

4.2. Simulation strategy

The changes in yields reported in the final rows of Table 2 for each region are used as input to our CGE model to simulate the RCP2.6 and RCP8.5 scenarios as a natural capital biased change in productivity, i.e. by shocking the parameter A^{NK} in equation E.3 which is set exogenously in our model using the total values from Table 2. This implies that the shock would impact only Sector A directly, but have general equilibrium impacts on the other sectors through prices and supply chain linkages. For simplicity the shock is fixed, permanent and it is introduced in the first period of the simulation. This allows us to compare the results from our counterfactual against a baseline where the shock does not take place.

5. RESULTS

5.1. Central case: aggregate impacts

Table 3: Long-run aggregated impacts for the RCP2.6 scenario

	Scotland	Western Scotland		Eastern Scotland	
	%	%	£	%	£
	LR	LR	C	LR	C
GDP	-0.03%	-0.03%	-125.00	-0.04%	-253.28
Consumption	0.01%	0.01%	44.30	0.00%	-5.24
Employment income	-0.01%	-0.01%	25.44	-0.02%	-5.24
Natural capital cost	4.82%	4.71%		4.93%	
Regional exports		-0.03%	-16.84	0.00%	-1.04
Regional imports		0.00%	-1.04	-0.03%	-16.84
Row exports	-0.02%	-0.01%	-14.85	-0.02%	-118.29
Row imports	-0.02%	-0.01%	-32.48	-0.03%	-103.97

Source: Authors calculations.

Table 3 presents the long-run impacts in key macroeconomic variables from the baseline data associated with the RCP2.6 scenario. Results are presented for key aggregate economic variables (down the rows of this table) and for two specific changes: long-run (LR)[20] percentage changes from the baseline, and as the present value of cumulative changes in £m (C) over the period considered in the simulation (2020-2100)[21], for Scotland in aggregate, as well as Western Scotland and Eastern Scotland.

Beginning with the aggregated Scottish results, the fall in land productivity associated with the changes in temperature and rainfall increases the cost of using land as input in

[20] The long run corresponds to a conceptual period where capital stocks have fully adjusted, and investment only covers annual depreciation.

[21] We follow the guidance from HM Treasury (2022) on long term discounting and adopt a declining discount rate.

production by 4.8%. This reflects the fact that it is now more costly to produce agricultural output as the combination of higher temperatures and reduced rainfalls decrease the productivity of land. This puts upward pressure on domestic prices and triggers a fall in aggregate demand, reflected in a 0.03% fall in aggregated Gross Value Added (GVA), corresponding to approximately £378m cumulatively. The contraction in demand is exacerbated by a fall in employment demand and income (-0.01%). Imports fall due to the reduction in production and export is negatively affected by the reduced competitiveness. Households demand increases slightly. This is due to the price reduction in all the non-agriculture outputs as demand falls. However, this is not sufficient to offset the reduced demand for export, government and investment goods.

5.2. Central case: regional impacts

The impacts on the two regions are qualitatively similar but quantitatively different. It is evident that Eastern Scotland is impacted more negatively. This is to be expected as Eastern Scotland's Sector A is larger relatively to Western Scotland's. Whilst at the macroeconomic levels the impacts are small, the agriculture sector is significantly impacted. For this reason, we report the long run % change in Sector A's key indicators in Table 4.

In Western Scotland, agricultural value-added falls by 1.59% corresponding to £100.2m by 2100. In Eastern Scotland it falls by 1.23% or (-£184.1m). Export to the rest of the world fall, particularly in Eastern Scotland (-£207.3m). Both regions increase their reliance on import from the rest of the world. Interregional trade increases as output of non-agriculture industries that is used as input in agriculture is now cheaper given the fall in the cost of labour. Western Scotland increases its dependence on imports from Eastern Scotland.

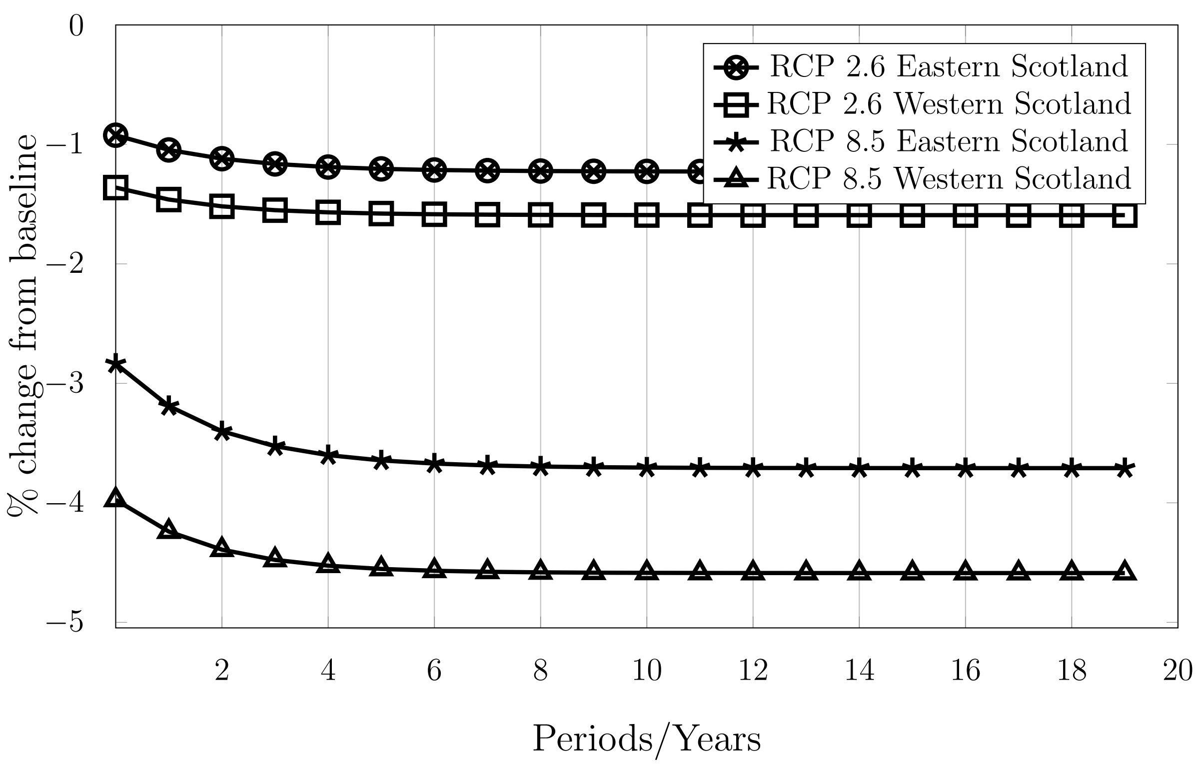
Figure 3 presents the percentage change in Sector's A GVA for the RCP2.6 and RCP8.5 scenarios. Recall that that each scenario is introduced as a permanent productivity shock which is unchanged throughout the simulation so that differences over time are given by the speed at which capital adjusts to the long-run level. In all the scenarios, the impact on GVA becomes more negative over time. Consistently with the results from Table 4, the RCP8.5 scenarios produces more negative long run impacts in the Eastern part of the nation. Given that RCP8.5 is a larger shock, the economy takes around 12 years to adjust, contrary to RCP2.6 where full long-run adjustment is reached after 10 years.

Table 4: Long-run aggregated impacts on Sector A under RCP2.6 scenario

	Western Scotland		Eastern Scotland	
	%	£m	%	£m
	LR	C	LR	C
Value added	-1.59%	-100.2	-1.23%	-184.1
Output price	0.50%		0.76%	
Consumption	-0.14%	-7.3	-0.23%	-12.5
Employment income	-0.66%	-11.0	-0.60%	-27.8
Regional exports	0.16%	13.5	0.83%	8.0
Regional imports	-0.99%	8.0	-1.50%	13.5
Row exports	0.16%	-48.3	0.25%	-207.3
Row imports	-1.59%	23.7	-1.23%	18.5

Source: Authors calculations.

Figure 3: Percentage change from the 2020 baseline in Sector's A GVA under RCP2.6 and RCP8.5 scenarios



5.3. Sensitivity analysis

Two sensitivity checks are conducted. First, the shock is introduced in each of the two regions individually. Second, the change in productivity associated with the RCP2.6 is applied to all the factors of production (total factor productivity), i.e., natural capital, physical capital and labour. This is consistent with previous studies that did not disaggregate natural capital (land) from other factors of production.

Table 5: Long-run aggregated impacts for the RCP2.6 scenario applied to each region individually.

	Western Scotland		Eastern Scotland	
	%	£m	%	£m
	LR	C	LR	C
5a. Western Scotland				
GDP	-0.02%	-93.64	0.00%	8.60
Consumption	0.01%	48.12	0.01%	18.96
Employment income	-0.00%	48.12	0.00%	18.96
Natural capital cost	3. 54%		0.32%	
Regional export	0.00%	-2.68	0.03%	26.68
Regional imports	0.03%	26.68	-0.00%	-2.68
Row export	-0.01%	-15.51	-0.00%	-18.51
Row imports	0.00%	-12.16	0.00%	19.65
5b. Eastern Scotland				
GDP	0.00%	-12.93	-0.04%	-198.18
Consumption	0.00%	-8.75	-0.01%	-20.84
Employment income	-0.02%	-8.75	-0.04%	-20.84
Natural capital cost	-0.03%		-0.02%	
Regional export	0.00%	-10.36	-0.02%	-23.87
Regional imports	0.00%	-23.87	-0.03%	-10.36
Row export	0.00%	2.35	-0.03%	-72.97
Row imports	0.00%	-14.18	-0.03%	-95.65

Source: Authors calculations.

Panel a in Table 5 reports results for when the RCP2.6 shock is applied to Western Scotland only. The impact on the region's GVA is marginally smaller than when the simulation is applied to the whole country. Interestingly, Western Scotland's imports from Eastern Scotland increase by approximately £26.7m cumulatively and this results in a small positive impact to the Eastern region. This highlights Scotland's reliance of the Eastern part of the country for agriculture. Panel b in Table 5 reports results for the case when the shock is applied to Eastern Scotland only. The impact on the region's GVA is marginally larger than when the whole country is impacted. This is due to a larger reduction in interregional trade as Western Scotland turns towards more domestically produced products.

Table 6: Long-run aggregated impacts for the RCP2.6 modelled as a total factor productivity shock.

	Western Scotland		Eastern Scotland	
	%	£m	%	£m
	LR	C	LR	C
GDP	-0.04%	-175.71	-0.06%	-401.26
Consumption	0.01%	45.54	-0.01%	-36.85
Employment income	-0.04%	45.54	-0.01%	-36.85
Natural capital cost	-0.02%		-0.06%	
Regional export	-0.04%	-20.42	-0.06%	-11.47
Regional imports	0.01%	-11.47	-0.01%	-20.42
Row export	-0.01%	-45.13	-0.01%	-230.57
Row imports	3.32%	-12.74	2.32%	-95.18

Source: Authors calculations.

Table 6 reports the impacts for the RCP 2.6 scenario modelled as a total factor productivity change in both regions. Not surprisingly, the impacts are larger across the board. However, these are qualitatively comparable to the results reported in Table 3.

6. DISCUSSION AND CONCLUSIONS

We have seen increasing concern about the consequences that future changes in the climate can have on the economy. Our research has focused on one route, principally, the impacts on regions of Scotland of changes in climate on the productivity of natural capital, proxied using the relationship between historical crop yields and temperature and rainfall. To the authors knowledge, there is only limited application of such a framework for water-abundant countries such as Scotland, however such analyses is critical if policy is to be developed appropriately to encourage mitigation of climate change and adaptation to the changing climate.

We find that the yields of crops have been impacted positively and negatively by climate over the last twenty years, and that projections of future climate scenarios suggests a reduction in crop yields for Wheat, Oats, Winter and Spring Barley. Our CGE results then show that economic activity falls under the overall reduction in land productivity. The regional decomposition of the results shows that the expected contraction is GVA in Eastern Scotland is almost twice as big as that in Western Scotland. This is because the Eastern region is more agriculture intensive.

Whilst our results are derived for the case of Scotland, the key takeaways could be applied to similar water abundant regions, especially where there is significant interregional dependence. Firstly, we show that water abundant regions are not immune from changes in agricultural yield driven by climate change. Albeit small, partly because they are derived in isolation, the results show that a region with the characteristics of Scotland will be negatively impacted. Secondly, we show that the sectoral composition of agricultural production plays an important role. Warmer summers may benefit crops that require prolonged higher temperatures in the growing season however the reduction in water availability will harm water intensive crops. Thirdly, we show the importance of trade dependences between regions in the same country. Agriculturally intensive regions may be hit more severely by changes in crop yields, but this negative impact will be transmitted to other dependant regions through higher food prices.

Whilst we believe that our results provide valuable guidance insights into the impact of climate change in a water abundant region it is important to recall that our method has a series of limitations. It is well known that large scale computational models such as CGE models are based simplifying assumptions that facilitate the solution of the model, such as perfect competition in markets where imperfections may exist and assumptions about agent's behaviour (Allan et al., 2021). Other limitations include the use of aggregated data and the sensitivity to key elasticity values. In this specific application we note that data availability has restricted the authors' ability to disentangle the impact of climate change driven changes in temperature and water availability on different types of crops and agriculture products.

To address some of the limitations of our work, this analysis could be extended in a number of ways. First, a crucial caveat of our results is that the simulation considers the impact of climate change in Scotland in isolation. This implies that the negative impacts calculated in this paper are the sole result of Scottish specific economic effects and do not take into account for potential spillover from the rest of the UK and the rest of the World. Second, the changes in productivity introduced assume that the current crop mix across regions in Scotland and by crop types is fixed at current levels. Various responses by crop growers exist which could mitigate the impacts of known changes in productivity, including changing the crop structure within regions. In addition, adaptation responses for existing crops could mean that the negative impacts of future projections could end up being lower than estimated here.

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APPENDIX

A. MAPPING UK REGIONS

Table A1: Mapping UK regions for crop and climate variables to a consistent geographic basis

Region	**Crop variables** (Source: DEFRA, 2022)	**Climate variables** (Source: Met Office, 2022)
1	Scotland	Scotland
2	Wales	Wales
3	Northern Ireland	Northern Ireland
4	East Midlands West Midlands	Midlands
5	Yorkshire and the Humberside North East	North East
6	North West and Merseyside	North West
7	Eastern	East Anglia
8	South West	England SW and South Wales
9	South East and London	England SE and Central

B. FULL SET OF RESULTS

B.1. Results using monthly interactions

Table B1: Effect of rain and temperature on crop yield

	Dependent variable is log of the yields of			
	Wheat	Oats	Winter Barley	Spring Barley
December × log(Rain)	-0.27	-0.35	-0.13	-0.32
	(0.12)*	(0.13)**	(0.09)	(0.11)**
January × log(Rain)	-0.19	-0.21	-0.20	-0.14
	(0.04)***	(0.11)*	(0.06)**	(0.10)
February × log(Rain)	-0.20	-0.07	-0.22	-0.23
	(0.06)***	(0.14)	(0.04)***	(0.08)**
June × log(Rain)	-0.15	0.05	-0.17	-0.03
	(0.05)**	(0.06)	(0.04)***	(0.03)
July × log(Rain)	0.08	0.23	-0.03	-0.03
	(0.09)	(0.20)	(0.07)	(0.10)
August × log(Rain)	0.06	0.11	0.01	-0.08
	(0.05)	(0.08)	(0.07)	(0.06)
December × log(Temp)	-0.13	0.10	-0.04	0.08
	(0.03)***	(0.07)	(0.07)	(0.09)
January × log(Temp)	-0.14	0.14	-0.04	0.06
	(0.03)***	(0.06)*	(0.08)	(0.09)
February × log(Temp)	-0.14	0.09	-0.02	0.08
	(0.03)***	(0.07)	(0.08)	(0.09)
June × log(Temp)	1.59	2.14	3.40	1.89
	(1.33)	(3.21)	(2.92)	(2.91)
July × log(Temp)	-4.20	0.99	-4.71	0.03
	(2.07)*	(3.73)	(1.52)**	(2.01)
August × log(Temp)	-0.19	-7.92	-5.86	-0.60
	(2.35)	(1.85)***	(2.11)**	(3.01)
December × $(\log(\text{Rain}))^2$	0.03	0.04	0.02	0.03
	(0.01)*	(0.01)**	(0.01)	(0.01)**
January × $(\log(\text{Rain}))^2$	0.02	0.02	0.02	0.01
	(0.01)***	(0.01)	(0.01)**	(0.01)
February × $(\log(\text{Rain}))^2$	0.03	0.00	0.02	0.02
	(0.01)***	(0.02)	(0.01)***	(0.01)**
June × $(\log(\text{Rain}))^2$	0.01	-0.01	0.02	0.00
	(0.01)	(0.01)	(0.01)***	(0.01)
July × $(\log(\text{Rain}))^2$	-0.01	-0.02	0.01	0.01
	(0.01)	(0.02)	(0.01)	(0.01)
August × $(\log(\text{Rain}))^2$	-0.01	-0.02	-0.00	0.01
	(0.01)	(0.01)**	(0.01)	(0.01)
December × $(\log(\text{Temp}))^2$	0.04	0.04	0.02	0.02
	(0.03)	(0.05)	(0.06)	(0.06)
January × $(\log(\text{Temp}))^2$	0.04	0.03	0.02	0.01
	(0.02)	(0.04)	(0.03)	(0.04)
February × $(\log(\text{Temp}))^2$	0.03	0.02	0.02	0.03
	(0.01)*	(0.03)	(0.02)	(0.02)
June × $(\log(\text{Temp}))^2$	-0.32	-0.27	-0.72	-0.32
	(0.28)	(0.62)	(0.55)	(0.54)
July × $(\log(\text{Temp}))^2$	0.81	-0.24	0.92	-0.01
	(0.38)*	(0.70)	(0.28)**	(0.38)
August × $(\log(\text{Temp}))^2$	0.09	1.26	1.10	0.09
	(0.42)	(0.38)**	(0.35)**	(0.53)
log(Rain, Temp, Sun)	✓	✓	✓	✓
$(\log(\text{Rain, Temp, Sun}))^2$	✓	✓	✓	✓
Month FEs × log(Sun)	✓	✓	✓	✓
Month FEs × $(\log(\text{Sun}))^2$	✓	✓	✓	✓
Region FEs × Month FEs	✓	✓	✓	✓
Year FEs × Month FEs	✓	✓	✓	✓
Region FEs × Year trend	✓	✓	✓	✓
N	2369	2369	2369	2369
Mean dependent variable	2.01	1.71	1.86	1.65
Base period	Aut/Apr	Aut/Apr	Aut/Apr	Aut/Apr
Included years	2000-2021	2000-2021	2000-2021	2000-2021
R^2	0.85	0.63	0.79	0.76
Adjusted R^2	0.82	0.55	0.75	0.70

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors (in parentheses) are clustered at the Region level. Here we use individual months instead of grouping months across summer and winter periods of the growing seasons.

B.2. Results clustering standard errors at the Region-Year level

Table B2: Effect of rain and temperature on crop yield

	Dependent variable is log yields of			
	Wheat	Oats	Winter Barley	Spring Barley
	(1)	(2)	(3)	(4)
Winter × log(Rain)	-0.21	-0.21	-0.19	-0.21
	(0.06)***	(0.09)**	(0.07)***	(0.07)***
Summer × log(Rain)	-0.09	0.05	-0.14	-0.06
	(0.05)*	(0.06)	(0.06)**	(0.05)
Winter × log(Temp)	-0.14	0.11	-0.04	0.06
	(0.07)*	(0.10)	(0.10)	(0.08)
Summer × log(Temp)	-1.19	2.20	-1.86	1.14
	(1.34)	(1.94)	(2.02)	(2.08)
Winter × $(\log(\text{Rain}))^2$	0.02	0.02	0.02	0.02
	(0.01)***	(0.01)**	(0.01)**	(0.01)**
Summer × $(\log(\text{Rain}))^2$	0.01	-0.01	0.02	0.01
	(0.01)	(0.01)	(0.01)**	(0.01)
Winter × $(\log(\text{Temp}))^2$	0.04	0.03	0.02	0.02
	(0.03)	(0.04)	(0.03)	(0.03)
Summer × $(\log(\text{Temp}))^2$	0.24	-0.43	0.36	-0.21
	(0.25)	(0.35)	(0.37)	(0.38)
log(Rain, Temp, Sun)	✓	✓	✓	✓
$(\log(\text{Rain, Temp, Sun}))^2$	✓	✓	✓	✓
Season FEs × log(Sun)	✓	✓	✓	✓
Season FEs × $(\log(\text{Sun}))^2$	✓	✓	✓	✓
Region FEs × Month FEs	✓	✓	✓	✓
Year FEs × Month FEs	✓	✓	✓	✓
Region FEs × Year trend	✓	✓	✓	✓
Region-Year	198	198	198	198
N	2369	2369	2369	2369
Mean dependent variable	2.01	1.71	1.86	1.65
Base period	Aut/Spr	Aut/Spr	Aut/Spr	Aut/Spr
Included years	2000-2021	2000-2021	2000-2021	2000-2021
R^2	0.85	0.63	0.79	0.75
Adjusted R^2	0.82	0.55	0.75	0.71

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors are in parentheses and allow for clustering of the model error at the Region-Year level. All our specifications, including controls and fixed effects, are as in Table 1.

B.3. Results allowing for spatial correlation in the distance dimension

Table B3: Effect of rain and temperature on crop yield

	Dependent variable is log yields of			
	Wheat	Oats	Winter Barley	Spring Barley
	(1)	(2)	(3)	(4)
Winter × log(Rain)	-0.21	-0.21	-0.19	-0.21
	(0.07)***	(0.08)**	(0.07)***	(0.07)***
Summer × log(Rain)	-0.09	0.05	-0.14	-0.06
	(0.06)	(0.07)	(0.06)**	(0.05)
Winter × log(Temp)	-0.14	0.11	-0.04	0.06
	(0.05)**	(0.08)	(0.09)	(0.07)
Summer × log(Temp)	-1.19	2.20	-1.87	1.14
	(1.55)	(2.17)	(2.32)	(2.17)
Winter × $(\log(\text{Rain}))^2$	0.02	0.02	0.02	0.02
	(0.01)***	(0.01)**	(0.01)***	(0.01)***
Summer × $(\log(\text{Rain}))^2$	0.01	-0.01	0.02	0.01
	(0.01)	(0.01)	(0.01)**	(0.01)
Winter × $(\log(\text{Temp}))^2$	0.04	0.03	0.02	0.02
	(0.02)*	(0.04)	(0.03)	(0.03)
Summer × $(\log(\text{Temp}))^2$	0.25	-0.43	0.36	-0.21
	(0.30)	(0.39)	(0.42)	(0.40)
log(Rain, Temp, Sun)	✓	✓	✓	✓
$(\log(\text{Rain, Temp, Sun}))^2$	✓	✓	✓	✓
Season FEs × log(Sun)	✓	✓	✓	✓
Season FEs × $(\log(\text{Sun}))^2$	✓	✓	✓	✓
Region FEs × Month FEs	✓	✓	✓	✓
Year FEs × Month FEs	✓	✓	✓	✓
Region FEs × Year trend	✓	✓	✓	✓
distance cutoff	500	500	500	500
N	2369	2369	2369	2369
Mean dependent variable	2.01	1.71	1.86	1.65
Base period	Aut/Spr	Aut/Spr	Aut/Spr	Aut/Spr
Included years	2000-2021	2000-2021	2000-2021	2000-2021
R^2	0.85	0.63	0.79	0.75

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. p-values are in parentheses with Conley standard errors, which allow for spatial correlation in the distance dimension. All our specifications, including controls and fixed effects, are as in Table 1.

C. SECTORS REPRESENTED IN THE CGE MODEL

A	Agriculture, forestry and Mining and quarrying
B_E	Electricity, gas… + Water supply, sewerage…
C	Manufacturing
F	Construction
G_I	Wholesale and retail trade + Transportation + Accommodation and food service
J	Information and communication
K_L	Financial and insurance activities, real estate
M_N	Professional activities + Administrative and support service activities
O_Q	Public administration and defence + Education + Health
R_U	Arts + Other services + Activities of households as employers… + Activities of extraterritorial org. and bodies

D. ADJUSTING NATURAL CAPITAL IN SCOTTISH-WATER CGE

We are seeking a methodology to identify implicit payments to water-related natural capital inputs to the primary sector in a two-region set of Scottish IO accounts (identified as West-East and using NUTS2 geographic boundaries). No such record currently exists for the data required, so use of existing data sources is required. We require, payments to land-related natural capital inputs in Scotland; Distinguish between payments appropriate for West and East areas; Disaggregation of natural capital inputs in existing IO/SAM and CGE.

D.1. Estimate of land-related natural capital inputs in Scotland

Scottish natural capital accounts are produced by ONS[22] and contain details of services produced from natural assets covering the period 1998 to 2019. There are three classes of ecosystem services, relating to provisioning services ("ecosystem services create products that include food, water, and materials. These are produced by nature, extracted, and then consumed by society."), regulating services ("an ecosystem benefit, which moderates natural phenomena. Regulating services include cleaning the air, sequestering carbon and regulating water flows to prevent flooding") and cultural services ("non-material, experiential benefits people obtain from natural capital, such as recreation and aesthetic experience.").

Similar to previous work on natural capital, we look solely at provisioning services provided by natural capital, and limit the scope of these for this analysis to those which are related to natural capital related to its natural capital directly related to production from farmland. This limits us to "agricultural biomass": "the value of crops, fodder and grazing which support Scottish agricultural production" and "water abstraction".

[22] Office for National Statistics (2021), Scottish natural capital accounts: supplementary information, published 17th June 2021, online at https://www.ons.gov.uk/economy/environmentalaccounts/datasets/scottishnaturalcapitalaccountssupplementaryinformation.

The monetary value of the service provided by agricultural biomass natural capital is derived as follows: "This is the surplus value to the agricultural industry after all costs have been considered. Estimated at an aggregate scale, it may include non-agricultural aspects of farm businesses." In 2017, it was valued at £562 million.

The monetary value of the water abstraction provisioning service provided is derived "from industry level data on the collection, treatment, and distribution of water for domestic and industrial needs. This valuation fluctuates year on year but was estimated to be £206 million in 2017, which is 6% of the UK annual value."

Table D1: Natural capital provisioning services, £million 2019 prices

Provisioning services	2014	2015	2016	2017	2018	Average*
Agricultural biomass	612	482	548	562	-	551
Water abstraction	164	103	204	206	-	139
Total	**776**	**585**	**752**	**768**	-	**690**
Other provisioning services						
Fish capture	-	133	271	299	243	234
Fossil fuels	4971	-1261	581	4341	10106	2158
Minerals	22	25	23	77	-	37
Timber	155	168	149	157	222	157
Renewables	117	129	153	157	-	139

Source: ONS (2021) see footnote 14.
Notes: * = average taken over 2014 to 2017.

D.2. Split by region

Various pieces of information exist on the pattern of agricultural land between West and East Scotland. These are summarised in Table 2, which draws information from Scottish Agricultural Tables, June 2020 edition (https://www.gov.scot/publications/economic-report-on-scottish-agricultur

Table D2: Splits by region

	Holdings (number)	**Total agricultural areas (hectares)**	**Total grass and rough grazing (hectares)**	**Crops and fallow (hectares)**	**Standard outputs, £**
West	34,244	4,310,153	3,794,475	97,378	1,049,825,882
East	17,619	1,930,756	1,247,577	482,284	1,603,481,339
Total	51,863	6,240,908	5,042,053	579,661	2,653,307,221
West (%)	66.03%	69.06%	75.26%	16.80%	39.57%
East (%)	33.97%	30.94%	24.74%	83.20%	60.43%

Notes: Standard Outputs (SO) give the value (in £'s) of crops and animals without including production costs. West refers to "North West" comprising Shetland, Orkney, Na h-Eileanan Siar and Highland, and "South West" comprising East Central, Argyll and Bute, Clyde Valley, Ayrshire and Dumfries and Galloway. East comprises, "North East", specifically Grampian and "South East" (Tayside, Fife, Lothian and Scottish Borders).

[23] Online at https://www.gov.scot/publications/economic-report-on-scottish-agriculture-tables-2020-edition/.

E. COMPLETE MODEL LISTING

Prices

$$PM_{r,i,t} = \overline{PM}_{r,i} \tag{E.1}$$

$$PI_{r,i,t} = PQ_{r',i,t} \tag{E.2}$$

$$PQ_{r,i,t} = \frac{PR_{r,i,t} \bullet R_{r,i,t} + PI_{r,i,t} \bullet MVI_{r,i,t} + PM_{i,t} \bullet M_{i,t}}{R_{r,i,t} + MVI_{r,i,t} + M_{r,i,t}} \tag{E.3}$$

$$PIR_{r,j,t} = \frac{R_{r,j,t} \bullet PR_{r,j,t} + MVI_{r,i,t} \bullet PI_{r,i,t}}{R_{r,j,t} + MVI_{r,i,t}} \tag{E.4}$$

$$PY_{r,j,t} \bullet a^{Y}_{r,j} = \left(PR_{r,j,t} \bullet \left(1 - btax_{r,j} - sub_{r,j} - dep_{r,j}\right) - \sum_i a^{V}_{r,i,j} PQ_{r,j,t} \right) \tag{E.5}$$

$$UCK_{r,t} = Pk_{r,t} \bullet (r_r + \delta_r) \tag{E.6}$$

$$Pc^{1-\sigma^c}_{r,t} = \sum_j \delta^{f}_{r,j} \bullet PQ^{1-\sigma^c}_{r,j,t} \tag{E.7}$$

$$Pg^{1-\sigma^g}_{r,t} = \sum_j \delta^{g}_{r,j} \bullet PQ^{1-\sigma^g}_{r,j,t} \tag{E.8}$$

$$Pv^{1-\rho}_{r,t} = \sum_i \sum_j a^{V}_{r,i,j} \bullet PQ^{1-\rho}_{r,i,t} \tag{E.9}$$

$$w^{b}_{r,t} = \frac{w_{r,t}}{(1 + \tau_{r,t})} \tag{E.10}$$

$$\ln\left(\frac{w^{b}_{r,t}}{cpi_{r,t}}\right) = b_r - 0.113 \ln\left(u_{r,t}\right) \tag{E.11}$$

$$rk_{r,j,t} = PY_{r,j,t} \bullet \alpha_{r,i} \bullet {A_r}^{Y\varrho_j} \bullet \left(\frac{Y_{r,j,t}}{K_{r,j,t}}\right)^{1-\varrho_j} \tag{E.12}$$

$$Pk_{r,t} = \frac{\sum_j PQ_{r,j,t} \bullet \sum_i KM_{r,i,j}}{\sum_i \sum_j KM_{r,i,j}} \tag{E.13}$$

Production technology

$$X_{r,i,t} = A_r^X \bullet \left[\delta_{r,i}^Y \bullet Y_{r,i,t}^{\rho_i^X} + \delta_{r,i}^V \bullet V_{r,i,t}^{\rho_i^X}\right]^{\frac{1}{\rho_i^X}} \tag{E.14}$$

$$Y_{r,j,t} = \left({A^X}_r^{\rho_j^X} \bullet \delta_{r,j}^Y \bullet \frac{PQ_{r,j,t}}{PY_{r,j,t}} \right)^{\frac{1}{1-\rho_j^X}} \bullet X_{r,j,t} \tag{E.15}$$

$$V_{r,j,t} = \left({A^X}_r^{\rho_j^X} \bullet \delta_{r,j}^V \bullet \frac{PQ_{r,j,t}}{Pv_{r,j,t}} \right)^{\frac{1}{1-\rho_j^X}} \bullet X_{r,j,t} \tag{E.16}$$

$$VV_{r,i,j,t} = a_{r,i,j}^V \bullet V_{r,i,t} \tag{E.17}$$

$$Y_{r,i,t} = {A^Y}_{i,r} \bullet \left[\alpha_{r,i} \bullet K_{r,i,t}^{\rho_i^Y} + \beta_{r,i} \bullet L_{r,i,t}^{\rho_i^Y} + \gamma_{r,i} \bullet NK_{r,i,t}^{\rho_i^Y}\right]^{\frac{1}{\rho_i^Y}} \tag{E.18}$$

$$L_{r,j,t} = \left({A^Y}_{i,r}^{\rho_j^Y} \beta_{r,i} \bullet \frac{PY_{r,j,t}}{w_{r,t}} \right)^{\frac{1}{1-\rho_j^Y}} \bullet Y_{r,j,t} \tag{E.19}$$

$$NK_{r,j,t} = \left({A^{NK}}_{i,r}^{\rho_j^Y} \bullet \gamma_{r,i} \bullet \frac{PY_{r,j,t}}{PNK_{r,j,t}} \right)^{\frac{1}{1-\rho_j^Y}} \bullet Y_{r,j,t} \tag{E.20}$$

Trade

$$VV_{r,i,j,t} = \gamma_{r,i,j}^{vv} \bullet \left[\delta_{r,i,j}^{vm} VM_{r,i,t}^{\rho_i^A} + \ \delta_{r,i,j}^{vir} VIR_{r,i,t}^{\rho_i^A}\right]^{\frac{1}{\rho_i^A}} \tag{E.21}$$

$$\frac{VM_{r,i,j,t}}{VIR_{r,i,j,t}} = \left[\left(\frac{\delta_{r,i,j}^{vm}}{\delta_{r,i,j}^{vir}} \right) \bullet \left(\frac{PIR_{r,i,t}}{PM_{r,i}} \right) \right]^{\frac{1}{1-\rho_i^A}} \tag{E.22}$$

$$VIR_{r,i,j,t} = \gamma_{r,i,j}^{vir} \bullet \left[\delta_{r,i,j}^{vi} VI_{r,i,t}^{\rho_i^A} + \ \delta_{r,i,j}^{vr} VR_{r,i,t}^{\rho_i^A}\right]^{\frac{1}{\rho_i^A}} \tag{E.23}$$

$$\frac{VR_{r,i,j,t}}{VI_{r,i,j,t}} = \left[\left(\frac{\delta_{r,i,j}^{vr}}{\delta_{r,i,j}^{vi}} \right) \bullet \left(\frac{PI_{r,i,t}}{PR_{r,i,t}} \right) \right]^{\frac{1}{1-\rho_i^A}} \tag{E.24}$$

$$E\_ROW_{r,i,t} = \overline{E\_ROW}_i \bullet \left(\frac{PE_{r,i}}{PR_{r,i,t}} \right)^{\sigma_i^x} \tag{E.25}$$

$$E\_INTER_{r,i,t} = MVI_{r',i,t} \tag{E.26}$$

$$E\_INTER_{r,i,t} + E\_ROW_{r,i,t} = E_{r,i,t} \tag{E.27}$$

Regional Demand

$$R_{r,i,t} = \sum_j VR_{r,i,j,t} + QHR_{r,i,t} + QVR_{r,i,t} + QGR_{r,i,t} \tag{E.28}$$

Total Production

$$X_{r,i,t} + M_{r,i,t} = \sum_j VV_{r,i,j,t} + QH_{r,i,t} + QV_{r,i,t} + QG_{r,i,t} + E_{r,i,t} \tag{E.29}$$

Households and other Domestic Institutions

$$YH_{r,t} = (1 - \tau_{r,t})\, L^S_{r,t}\, (1 - u_{r,t})\, w_{r,t} + TRF_{r,t} + \Pi_{r,t} \tag{E.30}$$

$$W_{r,t} = NFW_{r,t} + FW_{r,t} \tag{E.31}$$

$$NFW_{r,t}\,(1 + r_{r,t}) = NFW_{r,t+1} + (1 - \tau_{r,t})\, L^s_{r,t}\ (1 - u_{r,t})\, w_{r,t} + Trf_{r,t} \tag{E.32}$$

$$FW_{r,t}\,(1 + r_{r,t}) = FW_{r,t+1} + \Pi_{r,t} - S_{r,t} \tag{E.33}$$

$$Trf_{r,t} = PC_{r,t} \bullet\ \overline{Trf} \tag{E.34}$$

$$\Pi_{r,t} = d^h_r \bullet \sum_i rk_{r,i,t} K_{r,i,t} \tag{E.35}$$

$$S_{r,t} = mps_r \bullet YH_{r,t} \tag{E.36}$$

$$C_{r,t} = YH_{r,t} - S_{r,t} \tag{E.37}$$

$$QH_{r,i,t} = {\delta^f_{r,i}}^{\rho^c_i} \bullet \left(\frac{Pc_{r,t}}{PQ_{r,i,t}} \right)^{\rho^c_i} \bullet C_{r,t} \tag{E.38}$$

$$QH_{r,i,t} = \gamma^f_{r,i} \bullet \left[\delta^{hir}_{r,i} \bullet QHIR^{\rho^A_i}_{r,i,t} + \delta^{hm}_{r,i} \bullet QHM^{\rho^A_i}_{r,i,t} \right]^{\frac{1}{\rho^A_i}} \tag{E.39}$$

$$\frac{QHIR_{r,i,t}}{QHM_{r,i,t}} = \left[\left(\frac{\delta^{hir}_{r,i}}{\delta^{hm}_{r,i}} \right) \bullet \left(\frac{PM_i}{PIR_{r,i,t}} \right) \right]^{\frac{1}{1-\rho^A_i}} \tag{E.40}$$

$$QHIR_{r,i,t} = \gamma^{fir}_{r,i} \bullet \left[\delta^{hr}_{r,i} \bullet QHR^{\rho^A_i}_{r,i,t} + \delta^{hi}_{r,i} \bullet QHI^{\rho^A_i}_{r,i,t} \right]^{\frac{1}{\rho^A_i}} \tag{E.41}$$

$$\frac{QHR_{r,i,t}}{QHI_{r,i,t}} = \left[\left(\frac{\delta^{hr}_{r,i}}{\delta^{hi}_{r,i}} \right) \bullet \left(\frac{PI_{r,i,t}}{PR_{r,i,t}} \right) \right]^{\frac{1}{1-\rho^A_i}} \tag{E.42}$$

Government

$$FD_{r,t} = G_{r,t}Pg_{r,t} + \sum_{dngins} TRG_{dngins,r,t} \bullet Pc_{r,t} - \left(d_r^g \bullet \sum_i rk_{r,i,t} \bullet K_{r,i,t} + \sum_i IBT_{r,i,t} + \tau_{r,t} \bullet \sum_j L_{r,j,t} \bullet w_{r,t} + \overline{FE_r} \bullet \varepsilon_{r,t} \right) \quad \text{(E.43)}$$

$$QG_{r,i,t} = \delta_{r,i}^g \bullet G_{r,t} \quad \text{(E.44)}$$

$$QGR_{r,i,t} = QG_{r,i,t}; QGM_{r,i,t} = 0 \quad \text{(E.45)}$$

Capital formation demand

$$QV_{r,i,t} = \sum_j KM_{r,i,j} \bullet J_{r,j,t} \quad \text{(E.46)}$$

$$QV_{r,i,t} = \gamma_{r,i}^v \bullet \left[\delta_{r,i}^{qvm} \bullet QVM_{r,i,t}^{\rho_i^A} + \delta_{r,i}^{qvir} \bullet QVIR_{r,i,t}^{\rho_i^A} \right]^{\frac{1}{\rho_i^A}} \quad \text{(E.47)}$$

$$\frac{QVM_{r,i,t}}{QVIR_{r,i,t}} = \left[\left(\frac{\delta_{r,i}^{qvm}}{\delta_{r,i}^{qvir}} \right) \bullet \left(\frac{PIR_{r,i,t}}{PM_{r,i}} \right) \right]^{\frac{1}{1-\rho_i^A}} \quad \text{(E.48)}$$

$$QVIR_{r,i,t} = \gamma_{r,i}^{vir} \bullet \left[\delta_{r,i}^{qvi} \bullet QVI_{r,i,t}^{\rho_i^A} + \delta_{r,i}^{qvr} \bullet QVR_{r,i,t}^{\rho_i^A} \right]^{\frac{1}{\rho_i^A}} \quad \text{(E.49)}$$

$$\frac{QVR_{r,i,t}}{QVI_{r,i,t}} = \left[\left(\frac{\delta_{r,i}^{qvr}}{\delta_{r,i}^{qvi}} \right) \bullet \left(\frac{PI_{r,i,t}}{PR_{r,i,t}} \right) \right]^{\frac{1}{1-\rho_i^A}} \quad \text{(E.50)}$$

Time path of investment

$$I_{r,i,t} = v \bullet \left(KS_{r,i,t}^* - KS_{r,i,t} \right) \bullet \delta KS_{r,i,t} \quad \text{(E.51)}$$

$$KS_{r,i,t}^* = \left({A^Y}_{i,r}{}^{\rho_j^Y} \bullet \alpha_{r,i} \bullet \frac{PY_{r,j,t}}{rk_{r,j,t}} \right)^{\frac{1}{1-\rho_j^Y}} \bullet Y_{r,j,t} \quad \text{(E.52)}$$

Factors accumulation

$$KS_{r,i,t+1} = (1-\delta_r) \bullet KS_{r,i,t} + I_{r,i,t} \tag{E.53}$$

$$K_{r,i,t} = KS_{r,i,t} \tag{E.54}$$

$$LS_{r,t} = \overline{LS}_r \tag{E.55}$$

$$LS_{r,t} \bullet (1-u_{r,t}) = \sum_j L_{r,j,t} \tag{E.56}$$

$$NK_{i,r,t} = \overline{NKS}_{i,r} \tag{E.57}$$

Indirect taxes and subsidies

$$IBT_{i,t} = btax_i \bullet X_{i,t} \bullet PQ_{i,t} \tag{E.58}$$

Total demand for import and current account

$$MVM_{r,i,t} = \sum_j VM_{r,i,j,t} + QHM_{r,i,t} + QVM_{r,i,t} + QGM_{r,i,t} \tag{E.59}$$

$$MVI_{r,i,t} = \sum_j VI_{r,i,j,t} + QHI_{r,i,t} + QVI_{r,i,t} + QGI_{r,i,t} \tag{E.60}$$

$$M_{r,i,t} = MVM_{r,i,t} + MVI_{r,i,t} \tag{E.61}$$

$$TB_{r,t} = \sum_i M_{r,i,t} \bullet PM_{r,i} - \sum_i E_{r,i,t} \bullet PE_{r,i,t} + \varepsilon \bullet (REM_r + FE_r) \tag{E.62}$$

Assets

$$VF_{r,i,t} = \lambda_{r,i,t} \bullet K_{r,i,t} \tag{E.63}$$

$$D_{r,t+1} = (1+r_r) \bullet D_{r,t} + TB_{r,t} \tag{E.64}$$

$$Pg_{r,t+1} \bullet GD_{r,t+1} = \left[1 + r_r + \left(\frac{Pc_{r,t+1}}{Pc_{r,t}} - 1\right)\right] \bullet GD_{r,t} \bullet Pg_{r,t} + FD_{r,t} \tag{E.65}$$

Steady state conditions

$$\delta_r \bullet KS_{r,i,T} = I_{r,i,T} \tag{E.66}$$

$$R^k_{r,i,T} = \lambda_{r,i,T} \left(r_r + \delta_r\right) \tag{E.67}$$

$$FD_{r,T} = -\left[r_r + \left(\frac{Pc_{r,t+1}}{Pc_{r,t}} - 1\right)\right] \bullet Pg_{r,T} \bullet GD_{r,T} \tag{E.68}$$

$$TB_{r,T} = -r \bullet D_{r,T} \tag{E.69}$$

$$NFW_t r = \left(1 - \tau_t\right) L^s_t \ \left(1 - u_t\right) w_t + Trf_t \tag{E.70}$$

$$FW_{r,t} \bullet r_{r,T} = \Pi_{r,t} - S_{r,t} \tag{E.71}$$

Glossary

i,j $(i{=}j)$	the set of goods or industries
r,r' $(r{=}r')$	the set of regions (western Scotland, eastern Scotland)

Prices

$PY_{r,i,t}$	value added price
$PR_{r,i,t}$	regional price
$PQ_{r,i,t}$	output price
$PIR_{r,i,t}$	national commodity price (regional + interregional)
$PI_{r,i,t}$	price of interregional import
$PM_{r,i,t}$	price of ROW import
$rk_{r,i,t}$	rate of return to capital
$w_{r,t}$	nominal wage
$w^b_{r,t}$	after tax wage
$Pk_{r,t}$	capital good price
$UCK_{r,t}$	user cost of capital
$PNK_{i,r,t}$	Natural capital cost
$\lambda_{r,i,t}$	shadow price of capital
$Pc_{r,t}$	aggregate consumption price
$Pg_{r,t}$	aggregate price of Government consumption goods
ε	exchange rate [fixed]

Endogenous variables

$X_{r,i,t}$	total output
$R_{r,\ i,t}$	regional supply
$M_{r,i,t}$	total import
$MVM_{r,i,t}$	Rest of the world import
$MVI_{r,i,t}$	Interregional import

$E_{r,i,t}$	total export (ROW+ interregional)
$E\_{INTER}{r,i,t}$	Interregional export
$E\_{ROW}{r,i,t}$	Rest of the world export
$Y_{r,i,t}$	value added
$L_{r,i,t}$	labour demand
$K_{r,i,t}$	physical capital demand
$KS_{r,i,t}$	capital stock
$LS_{r,i,t}$	labour supply
$NK_{r,i,t}$	Natural capital
$VV_{r,i,j,t}$	total intermediate inputs in i and j
$V_{r,i,t}$	Total intermediate inputs in i
$VR_{r,i,j,t}$	regional intermediate inputs
$VM_{r,i,j,t}$	ROW intermediate inputs
$VIR_{r,i,j,t}$	national intermediate inputs (ROW + interregional)
$VI_{r,i,j,t}$	RUK intermediate inputs
$G_{r,i,t}$	aggregate government expenditure
$QG_{r,i,t}$	total government expenditure by sector i
$QGR_{r,i,t}$	regional government expenditure
$QGM_{r,i,t}$	government expenditure (ROW)
$FD_{r,T}$	fiscal deficit
$C_{r,t}$	aggregated household consumption
$QH_{r,i,t}$	total households consumption in sector i
$QHR_{r,i,t}$	regional consumption in sector i
$QHI_{r,i,t}$	interregional consumption in sector i
$QHIR_{r,i,t}$	domestic + interregional consumption in sector i
$QHM_{r,i,t}$	ROW import consumption in sector i
$QV_{r,i,t}$	total investment by sector of origin i
$QVR_{r,i,t}$	regional investment by sector of origin i
$QVM_{r,i,t}$	ROW investment demand
$QVIR_{r,i,t}$	national investment (regional + interregional)
$QVI_{r,i,t}$	Interregional investment demand
$I_{r,j,t}$	investment by sector of destination j
$J_{r,j,t}$	investment by destination j with adjustment cost
$u_{r,t}$	regional unemployment rate
$R^k_{r,i,t}$	marginal net revenue of capital
$S_{r,t}$	domestic non-government saving
$Trf_{r,t}$	households net transfer
$YH_{r,t}$	Household income
$TB_{r,t}$	current account balance

Exogenous variables

$\overline{REM}_{r,t}$	remittances for *Household*
$\overline{FE}_{r,t}$	remittances for the Government
$GSAV_{r,t}$	government saving

r_r	interest rate
$\overline{NKS}_{i,r}$	natural capital supply

Elasticities

σ	constant elasticity of marginal utility
ρ_i^X	elasticity between intermediate inputs and value added
ρ_i^Y	elasticity between capital and labour
ρ_i^A	elasticity in Armington function
σ_i^x	elasticity of export with respect to terms of trade

Parameters

$\delta_{r,i,j}^V$	Input-output coefficients for i used in j
$\delta_{r,j}^Y$	share of value added on production
$\delta_{r,j}^{Y,V}$	shares in CES output function in sector j
$\delta_{r,j}^{k,l}$	shares in value added function in sector j
$\alpha_{r,i}$	Share of capital
$\beta_{r,i}$	Share of labour
$\gamma_{r,i}$	Share of natural capital/land
${A^Y}_{i,r}$	Productivity parameter for primary factors
${A^{NK}}_{i,r}$	Productivity parameter for natural capital
$\delta_{r,i,j}^{vir,vm,vr,vi}$	shares parameters in CES function for intermediate goods
$\delta_{r,i,j}^{qvir,qvm,qvr,qvi}$	shares parameters in CES function for investment goods
$\delta_{r,i,h}^{hr,hm}$	shares parameters in CES function for households consumption
$\delta_{r,i}^{gr,gm}$	shares parameters in CES function for government consumption
$\gamma_{r,i,j}^{vv,vir}$	shift parameter in CES functions for intermediate goods
$\gamma_{r,i}^{f}$	shift parameter in CES function for households consumption goods
$\gamma_{r,i}^{g}$	shift parameter in CES function for government consumption
$btax_{r,i}$	rate of business tax
$KM_{r,i,j}$	physical capital matrix
mps_r	rate of saving
τ_r	rate of income tax
ρ	pure rate of consumer time preference
bb_r	rate of distortion or incentive to investment
δ_r	rate of depreciation