REGIONAL STUDIES, 2016
http://dx.doi.org/10.1080/00343404.2016.1167865

Impacts of regional productivity growth, decoupling and pollution leakage

Cathy Xin Cui[a], Nick Hanley[b], Peter McGregor[c], Kim Swales[d], Karen Turner[e] and Ya Ping Yin[f]

ABSTRACT

Impacts of regional productivity growth, decoupling and pollution leakage. *Regional Studies*. This paper examines the issues of decoupling regional economic growth and pollution and the extent to which pollution effects spillover regional/national borders. Specifically, a UK, regionally disaggregated, computable general equilibrium (CGE) model is used to investigate the relationship between economic growth and the level of CO_2 emissions posited by the 'environmental Kuznets curve' (EKC) conjecture using production accounting principle (PAP) and consumption accounting principle (CAP) environmental accounting methods. The simulation results suggest that at the regional level the existence of an EKC relationship depends on the source of regional growth and the how this relationship is specified.

KEYWORDS

regional computable general equilibrium (CGE) models; labour productivity; regional economic growth; environmental Kuznets curve (EKC); embedded pollution; carbon footprints

摘要

区域生产力成长的影响，去对偶化和污染外泄. *Regional Studies*. 本文检视将区域经济成长与污染去对偶化，以及污染的影响外溢至区域／国族边界外的程度之议题。本研究特别运用英国按区域分类的可计算一般均衡模型（CGE），探讨使用生产基础原则（PAP）和消费基础原则（CAP）的环境计算方法的'环境库兹涅茨曲线（EKC）'推测所假定的经济成长和CO2排放程度之间的关联性。模拟的结果显示，在区域层级，EKC关係的存在，取决于区域成长的来源和此一关係如何被具体指明。

关键词

区域可计算一般均衡（CGE）模型; 劳动生产力; 区域经济成长; 环境库兹涅茨曲线（EKC); 镶嵌的污染; 碳足迹

RÉSUMÉ

Les répercussions de la croissance de la productivité: le découplage et la pollution due aux fuites. *Regional Studies*. Cet article examine la question du découplage entre la croissance économique régionale et la pollution, ainsi que la question de savoir dans quelle mesure la pollution déborde les frontières régionales et nationales. Plus précisément, à

CONTACT

[a] cathy.x.cui@googlemail.com
Fraser of Allander Institute, Department of Economics, University of Strathclyde, Glasgow, UK.
[b] ndh3@st-andrews.ac.uk
Department of Geography and Sustainable Development, Irvine Building, University of St Andrews, St Andrews, UK.
[c] p.mcgregor@strath.ac.uk
Fraser of Allander Institute, Department of Economics, University of Strathclyde, Glasgow, UK.
[d] (**Corresponding author**) j.k.swales@strath.ac.uk
Fraser of Allander Institute, Department of Economics, University of Strathclyde, Glasgow, UK.
[e] karen.turner@strath.ac.uk
Centre for Energy Policy, Strathclyde International Public Policy Institute, University of Strathclyde, Glasgow, UK.
[f] y.p.yin@herts.ac.uk
Department of Economics, Social Sciences and Tourism, Business School, University of Hertfordshire, Hatfield, UK.

partir d'un modèle d'équilibre général calculable (Égc) du R-U, désagrégé à l'échelle régionale, on examine le rapport entre la croissance économique et le niveau des émissions de CO_2 avancé par l'hypothèse de 'la courbe environnementale de Kuznets' (Cek), en employant des méthodes de comptabilité environnementale suivant les principes comptables quant à la production (PAP; production accounting principle) et à la consommation (CAP; consumption accounting principle). Les résultats de la simulation laissent supposer que sur le plan régional la présence d'un rapport Cek dépend de l'origine de la croissance régionale et de comment on peut préciser ce rapport.

MOTS-CLÉS
modèles d'équilibre général calculables régionaux (Égc); productivité du travail; croissance économique régionale; courbe environnementale de Kuznets (Cek); pollution enchâssée; empreintes carbones

ZUSAMMENFASSUNG
Auswirkungen von regionalem Produktivitätswachstum, Entkoppelung und Übertragung von Umweltverschmutzung. *Regional Studies*. In diesem Beitrag untersuchen wir die Probleme bei der Entkoppelung des regionalen Wirtschaftswachstums von der Umweltverschmutzung sowie das Ausmaß, in dem sich die Auswirkungen der Umweltverschmutzung über regionale und nationale Grenzen hinwegsetzen. Insbesondere untersuchen wir mithilfe eines regional aufgegliederten berechenbaren allgemeinen Gleichgewichtsmodells (CGE) für Großbritannien die Beziehung zwischen dem Wirtschaftswachstum und dem Umfang der von der hypothetischen 'Umwelt-Kuznets-Kurve' (EKC) postulierten CO_2-Emissionen unter Verwendung der Ökobilanzierungsmethoden des Produktionsbilanzgrundsatzes und des Verbrauchsbilanzgrundsatzes. Die Ergebnisse der Simulation lassen darauf schließen, dass auf regionaler Ebene das Vorhandensein einer EKC-Beziehung von der Quelle des regionalen Wachstums und der Art der Festlegung dieser Beziehung abhängt.

SCHLÜSSELWÖRTER
regionale berechenbare allgemeine Gleichgewichtsmodelle (CGE); Arbeitsproduktivität; regionales Wirtschaftswachstum; Umwelt-Kuznets-Kurve (EKC); eingebettete Umweltverschmutzung; CO_2-Fußabdrücke

RESUMEN
Repercusiones del crecimiento de la productividad regional, disociación y fugas de contaminación. *Regional Studies*. En este artículo se analizan los problemas de la disociación del crecimiento económico regional y la contaminación, y en qué medida los efectos de la contaminación desbordan las fronteras regionales y nacionales. En concreto, mediante un modelo británico del equilibrio general computable disgregado regionalmente, analizamos la relación entre el crecimiento económico y el nivel de emisiones CO_2 postulado por la conjetura de la 'curva ambiental de Kuznets' (CAK) a partir de los métodos contables medioambientales del principio contable de la producción y del principio contable del consumo. Los resultados de la simulación indican que a nivel regional la existencia de una relación de la CAK depende de la fuente del crecimiento regional y el modo en que se especifica esta relación.

PALABRAS CLAVES
modelos del equilibrio general computable regional; productividad laboral; crecimiento económico regional; curva ambiental de Kuznets (CAK); contaminación incorporada; huellas de carbono

JEL D57, O18, Q56
HISTORY Received January 2015; in revised form March 2016

INTRODUCTION

Scotland is a devolved UK region with responsibility for many industrial development and environmental policy functions. To this end, the Scottish government has set itself challenging economic development targets (Scottish Government, 2015). However, it has also adopted a particularly strong environmental stance, setting targets to reduce greenhouse gas (GHG) emissions by 42% by 2020 and by 80% by 2050, relative to the 1990 level (Climate Change (Scotland) Act, 2009).

This paper uses a two-region (Scotland–Rest of the UK (RUK)) computable general equilibrium (CGE) model to investigate two key issues. First, is there tension between delivering on Scotland's regional economic development and environmental targets? Second, what are the economic and environmental spillovers to the other regions of the UK? These are important concerns as the UK central government is presently legislating for greater devolved powers to Scotland and other regions of the UK.

The paper introduces a step Harrod-neutral (labour-augmenting) technological improvement across all Scottish production sectors. The subsequent economic and environmental effects are then simulated using a two-region (Scotland–RUK) CGE model. A novel contribution is the use of such a modelling framework to calculate the changes in carbon emissions using both production (PAP) and consumption accounting principles (CAP).[1]

The aim is not to predict or track the actual economic and environmental path of the Scottish economy over time, which will be affected by a wide range of exogenous and endogenous economic, social, political and regulatory factors at the regional, national and global levels. If this were the aim then a more dynamic modelling approach would be required (Marin & Mazzanti, 2013; Musolesi & Mazzanti, 2014; Vollebergh, Melenberg, & Dijkgraaf, 2009). Rather the focus is solely on the interaction between an exogenous (assumed policy-driven) improvement in labour efficiency and the subsequent resulting endogenous changes in per capita gross domestic product (GDP) and CO_2 emissions holding other exogenous factors constant. CGE simulation is therefore complementary to the econometric work in this area. Whilst the paper considers in detail the Scottish case, the results should have general interest for devolved regional environmental and economic policy-making and the implications of adopting different environmental accounting procedures (Marin, Mazzanti, & Montini, 2012).

ECONOMIC GROWTH AND POLLUTION LEAKAGE

In the literature, productivity improvements have been identified as important mechanisms for decoupling economic growth from environmental damage. This is one possible reason for the suggested existence of an environmental Kuznets curve (EKC), the projected inverted 'U'-shaped relationship between total or per capita emissions and GDP (Jaffe, Newell, & Stavins, 2003).[2] Econometric work has attempted to isolate the constituent elements of the relationship between economic growth and the environment using the incidence, population, affluence, technology (IPAT) framework (Mazzanti & Zoboli, 2009; York, Rosa, & Dietz, 2003). Levinson (2009) takes an environmental accounting approach. It uses input–output data to decomposes the change in US airborne emissions over time into scale (size of the economy), composition (sectoral mix, including international trade) and technique (production and abatement technology) effects and finds that changes in technique are the main drivers of emissions reduction.

But even if the economy appears to follow an EKC, there is concern over potential pollution leakage. This is where environmental reductions in one jurisdiction are met by shifting the pollution generation elsewhere (Arrow et al., 1995). Measures such as pollution taxes applied in one country might result in increased emissions in other countries through changing incentives for the location of dirty industries when products and processes are mobile across international borders (Sheldon, 2006). This is problematic not only for the global control of GHG emissions but also in a nation-state where the devolution of policies to regions might render the achievement of national targets more difficult. CGE analyses that have investigated pollution leakage in response to carbon taxes or caps include Babiker (2005), Bruvoll and Faehn (2006), and Elliot, Kortum, Munson, Pérez, and Weisbach (2010).

There is also a literature on the relationship between pollution leakage and economic growth. The most basic argument is that within a particular economy, growth involving structural change to importing, rather than producing, manufactured goods could lead to a fall in domestic emissions but drive increased pollution in other parts of the world (Bruvoll and Faehn, 2006). However, this depends on the precise source and nature of growth and development. Using input–output decomposition, Levinson (2009) calculates that the transfer of polluting industries overseas accounted for around 10% of US emissions reductions over the period 1987–2001. Using both historical data and CGE modelling, Faehn and Bruvoll (2009) find that economic growth was not associated with leakage impacts in the form of net imports of 'dirty' goods.

Current international agreements, such as the Kyoto Protocol and Copenhagen Accord, along with the recent UNFCCC COP20/CMP10 meeting in Lima, Peru, in advance of Paris 2015, adopt the production accounting principle (PAP) which covers all the CO_2 generated directly in production and consumption within a given territory. On the other hand, the consumption accounting principle (CAP) quantifies the CO_2 emissions embodied in the public and private consumption in a particular territory, independently of where these emissions occur.

At the UK level, the Department for Energy and Climate Change (DECC) and the Department for Environment, Food and Rural Affairs (DEFRA) (2012) have regularly engaged in, and provided advice on, carbon footprint accounting, and the House of Commons Energy and Climate Change Committee (2012) has recommended that consumption-based measures should be incorporated into the policy process. Further, the Scottish Government (2011) has explicitly identified the goal of lowering the Scottish GHG and carbon footprints in its emissions-reduction strategy. The consumption accounting approach is the most rigorous way to capture the economy's carbon footprint and this is used in this paper to control for pollution leakage between the UK regions and from the UK regions to the rest of the world (ROW). CGE studies have mainly taken a production-accounting approach to measuring pollution impacts, whereas full consumption-based accounting of carbon emissions is a more common development in the input–output literature (see Wiedmann, 2009, for a review).

Turner and Hanley (2011) question the definition of the EKC as a relationship between absolute pollution levels and per capita GDP. This issue is important where population change is a key element of the growth story; it is quite feasible for per capita GDP to rise whilst population falls. Therefore, in this paper the EKC conjecture is expressed as an inverted 'U'-shaped relationship between per capita pollution and per capita GDP; at high levels of GDP per head the conjecture predicts a fall in pollution per head. Here the territorial unit is the region and the target pollutant is CO_2 emissions, which are measured using both the PAP and CAP conventions.

Looking across the various modelling approaches, a number of conditions generally emerge as important for determining the degree of pollution leakage. These are compositional changes in the domestic economy, factor mobility and the pollution content of imports which substitute for domestic production. These are all allowed for in the model described below, along with endogenous changes in the scale of economic activity in both the home regional economy and its regional trading partner. The paper is differentiated by narrowly focusing on the technological progress argument underlying the EKC hypothesis.

THE AMOSRUK 2-REGION CGE MODELLING FRAMEWORK

AMOSRUK is a CGE model of the UK economy with two endogenous regions, Scotland and the RUK, and one exogenous region, the ROW. It is calibrated on a six-sector interregional social accounting matrix (SAM) for 2004, which provides a 'snapshot' of the Scottish and RUK economies and related CO_2 emissions generation for that year.[3] The six sectors/commodities model are detailed in Table 1.[4] Harrigan, McGregor, Perman, Swales, and Yin (1991) give a full description of the initial AMOS framework, and Turner, Gilmartin, McGregor, and Swales (2012) provide a condensed listing of the AMOSRUK variant used here. Greenaway, Leyborne, Reed, and Whalley (1993), Partridge and Rickman (2010), and Bergman (2005) review general, regional and environmental CGE modelling frameworks respectively. This section summarizes the main features of the interregional CGE model relevant to the scenarios reported in this paper.

There are four main components of final demand: household consumption, investment, government expenditure and exports to the ROW. Household consumption is a linear homogenous function of income; investment is explained below, while government expenditure is exogenous and unchanging.[5] Both interregional and international exports are price sensitive. However, while non-price determinants of exports to the ROW are taken to be exogenous, export demand to the other UK region is fully endogenous, depending not only on relative prices but also on the structure of all the elements of intermediate and final demand in the other region.

In production, a local composite of intermediate inputs is combined with a composite of imports from the other region and the ROW via an Armington link (Armington, 1969). This means that domestic products and imported goods are treated as imperfect substitutes, with the degree of substitutability determined exogenously. However, while the commodity composition of Scottish and RUK intermediates to each sector varies with local prices, the commodity composition of ROW imports to individual sectors and to final consumption is fixed.

In the current application, all Armington import elasticities are set at 2.0 (Gibson, 1990). The composite intermediate input is then combined with labour and capital (value added) to determine each sector's gross output. Production functions at each level of the production hierarchy can be constant elasticity of substitution (CES), Cobb–Douglas or Leontief. The simulations in this paper use CES production functions at the value-added level, where the elasticity of substitution equals a mid-range value of 0.5. This figure is informed by the literature where substitutability between labour and capital takes a range of values less than 1. At the gross-output level the elasticity takes the value of 0.3, informed by Harris (1989) with some sensitivity at the value-added level discussed in the seventh and eighth sections and examined in detail in an earlier version of this paper.[6] Leontief productions functions are adopted at the domestic intermediate-inputs level in each region (with the domestic intermediates composite substituting with an imports composite under the Armington assumption above).

The capital stock in each region is determined by sector-specific investment where in each period investment demand from each sector is a proportion of the difference between actual and desired capital stock. The desired capital stock is itself a function of commodity output, the nominal wage and the user cost of capital. The speed of adjustment parameter is the proportion of the gap between a regional industry's actual and desired capital stock that is filled between any two periods. This takes the value of 0.5 in this paper. Thus, in response to an exogenous shock, investment acts over time to readjust capital stocks to their new optimal values.

In the current application there is assumed to be no natural population increase and no international migration. However, the regional labour forces adjust through interregional migration between Scotland and the RUK in response to changes in the regional real-wage and unemployment differentials. This flow-equilibrium migration function is based on an extension of the Harris and Todaro (1970) parameterization based on UK regional econometric work reported by Layard, Nickell, and Jackman (1991),

Table 1. Sectoral disaggregation with the corresponding UK IO (UK IOC) and Standard Industrial (SIC) classification codes.

Sector/commodity output	UK IOC	SIC (2003)
1. Energy	4, 35, 85–86	10, 23, 40.1–40.3
2. Extraction, quarrying, construction and water supply	5–7, 87–88	11–14, 41, 45
3. Agriculture and fishing	1–3	01–02 (Part), 05.01–05.02
4. Manufacturing	8–84, except 35	15–37, except 23
5. Retail, distribution and transport	89–99	50–52, 55, 60.1–60.3, 61–63, 64.1–64.2
6. Other services	100–123	65–75, 80, 85.1–85.3, 90–93, 95

taking the form:

$$\ln\left[\frac{m^S}{L^S}\right] = \delta - 0.08[\ln u^S - \ln u^R] + 0.06\left[\ln\left[\frac{w^S}{\text{cpi}^S}\right] - \ln\left[\frac{w^R}{\text{cpi}^R}\right]\right] \quad (1)$$

In each period, within each region, real wages are determined via a wage curve and labour can move freely between sectors. The wage curve reflects the workers' bargaining power in the form of a negative relationship with the regional unemployment rate and is parameterized based on work by Layard et al. (1991) and supported by subsequent studies (Galvez, 2014):

$$\ln\left[\frac{w^i}{\text{cpi}^i}\right] = \beta^i - 1.113 \ln u^i \quad (2)$$

Direct CO_2 emissions' generation in household consumption and each production sector are related to energy use where appropriate and otherwise to output or total final expenditure. For the CAP measure, emissions embodied in imports from the ROW to each region are determined using a dataset provided by the Organisation for Economic Co-operation and Development (OECD) (Turner et al., 2011) and are adjusted to reflect total emissions (kilotonnes) per £1 million of imports to each production sector and household final consumption in the two endogenous regions. This involves weighting output-CO_2 intensities for the six external commodities based on the commodity and country source composition of imports in each.

Turner et al. (2012) give fuller details on the specification of the environmental component of the AMOSRUK model. This paper applies CGE techniques to simulate changes in the underlying input–output structure of the economy in each period following a shock and then applies standard interregional accounting methods to compute CAP at the UK level (Miller & Blair, 2009; Turner, Lenzen, Wiedmann, & Barrett, 2007).[7] Changes in imports are also determined via the CGE analysis, to which the import intensities drawn from the OECD data are applied.

SIMULATION STRATEGY

Labour productivity is increased in the most straightforward manner; that is through a 5% Harrod-neutral (labour augmenting) step increase in the efficiency of value added production across all Scottish production sectors. This value broadly represents the difference between the present Scottish labour productivity level and that in the RUK, so that if Scotland were to achieve UK average productivity levels, such an improvement would be required (Office for National Statistics (ONS), 2014).[8] At present, the relevant policy option most directly under the control of the Scottish government is skills generation, which would precisely impact labour productivity in this manner.

At the outset, both the Scotland and the RUK regional economies are assumed to be in long-run equilibrium and the shock is introduced in period 1. Both economies adjust to a new long-run equilibrium through a series of temporary equilibria, each of which is interpreted as one year.[9] While period-by-period results are reported in the Appendix in the supplemental data online, the focus is primarily on two conceptual time periods. The first is the short run (SR), which is the period immediately after the introduction of the efficiency improvement. In this period capital stocks are fixed both to the region and the specific industry. The second is the long run (LR) where labour and capital stocks have fully adjusted, both across regions and sectors, to the shock.

Given that one simulates the impact of a single exogenous disturbance, all changes reported are attributable solely to the direct, indirect and induced effects of that disturbance. That is, in the absence of an external shock the model continuously recreates the base-year data, period by period. The results are reported either as percentage or as absolute changes from the base-year (2004) equilibrium values, depending on pedagogic considerations.

SIMULATION RESULTS

A Harrod-neutral efficiency improvement in one region, Scotland, triggers a number of general equilibrium economic and environmental effects that operate across both regions. These changes are shown in Table 2, which gives the initial absolute values and the resulting SR and LR percentage changes in variables for Scotland, the RUK and the UK as a whole. Appendix Figures A1–A6 in the supplemental data online identify the time paths of key economic and environmental variables for Scotland and the RUK. The economic variables comprise GDP, GDP per capita, real take-home wage, population and output disaggregated by sector. The environmental variables are the total, per capita and per £ million GDP CO_2 emissions, under PAP and CAP accounting conventions.

In interpreting the results the authors follow a broad IPAT approach in disaggregating the per capita CO_2 figures into changes in GDP per head and the CO_2 intensity of GDP. This simulation approach should be seen as complementary to econometric results which attempt to identify regional environmental economic and environmental interaction and spillovers (Costantini, Mazzanti, & Montini, 2013; Mazzanti & Montini, 2010).

Economic impacts in the host economy (Scotland)

The increase in labour productivity improves Scottish competitiveness, so that Scottish GDP will increase. However, the impact on employment is less clear cut. There is a rise in labour demand. This is generated by the combination of the output effect, which is driven by increased competitiveness and the substitution effect towards the employment of labour, when measured in efficiency units. But the direct efficiency effect, the fact that a given output level can, in principle, be achieved now with less labour, will tend to reduce the demand for labour in physical units (number of employees).

Table 2. Impacts of a 5% increase in Scottish labour productivity on Scottish and rest of the UK (RUK) key economic and headline CO_2 variables (% change from base-year values).

	Scotland			RUK			UK		
	Base	SR (%)	LR (%)	Base	SR (%)	LR (%)	Base	SR (%)	LR (%)
GDP (£, millions)	88,351	3.18	7.76	967,744	0.02	−0.20	1,056,095	0.29	0.47
Household consumption (£, millions)	54,923	0.88	3.76	621,187	0.01	−0.27	676,109	0.08	0.06
Aggregate consumption (households and government, £, millions)	79,630	0.61	2.59	846,395	0.01	−0.19	926,025	0.06	0.04
Investment (£, millions)	12,949	8.57	6.11	174,508	−0.05	−0.17	187,457	0.54	0.27
Consumer price index (CPI)	1000	−1.43	−3.21	1000	−0.13	−0.22			
Exports to other region (£, millions)	34,876	3.02	7.85	36,480	0.66	0.07			
Imports from other region (£, millions)	36,480	0.66	0.07	34,876	3.02	7.85			
Exports to the ROW (£, millions)	15,706	2.96	7.77	249,595	0.20	0.36	265,301	0.36	0.79
Imports from the ROW (£, millions)	18,329	0.31	−0.37	304,359	−0.19	−0.61	322,688	−0.16	−0.60
Real consumption wage (£)	15,814	0.11	0.19	17,392	0.02	0.17			
Total employment (thousands)	2108	0.11	3.71	21,681	0.02	−0.25	23,789	0.03	0.10
Unemployment rate (%)	6437	−1.63	−1.63	5220	−0.35	−1.53			
Total population (thousands)	5078	0.00	3.59	54,756	0.00	−0.33	59,834	0.00	0.00
PAP CO_2 emissions (tonnes)	52,790,125	2.46	6.96	578,294,304	0.06	−0.02	631,084,429	0.26	0.56
PAP CO_2 emissions per capita	10.4	2.46	3.25	10.6	0.06	0.31	10.5	0.26	0.56
PAP CO_2 emissions per £1 million GDP	596	−0.70	−0.75	598	0.04	0.17	598	−0.03	0.09
CAP CO_2 emissions (tonnes)	62,659,082	1.44	3.13	626,179,641	0.02	0.04	688,838,723	0.15	0.32
CAP CO_2 emissions per capita	12.3	1.44	−0.44	11.4	0.02	0.37	11.5%	0.15	0.32
CAP CO_2 emissions per £1 million GDP	709	−1.69	−4.30	647	0.00	0.24	652	−0.14	−0.15

Note: CAP, consumption accounting principle; GDP, gross domestic product; PAP, production accounting principle; ROW, rest of the world.

If there is a net increase in the demand for employees, this generates a short-run increase in the real wage, and a fall in the unemployment rate, producing net in-migration, which further stimulates employment and economic activity through subsequent downward pressure on wage rates. As the economy expands, with the short-run supply constraints relaxed through in-migration of labour and investment in capital stock, the labour incomes received by households will rise. This further increases household consumption demand in all sectors of the economy.[10]

This complex pattern of effects underlies the results reported in the first three columns of Table 2. There is a very small, 0.11%, short-run increase in employment. However, as the constraints on capital stock and labour supply are relaxed, through investment and migration, the Scottish economy expands with a further net increase in labour demand. The long-run increase in Scottish employment is 3.71%. The rise in the real wage and the fall in unemployment rate is the short-run trigger for immigration from the RUK to Scotland. This continues until the initial differentials in the Scottish wage and unemployment rates, relative to their UK counterparts, are restored in long-run equilibrium. The real wage increases up to period 5, where it is 0.77% higher than its base-year value, but subsequently moves back towards its original value recording a long-run increase of only 0.19%. Scottish GDP increases monotonically, with a long-run rise of 7.76% over the base-year value. As a metric, this would correspond to between three and four years of average growth in the decade from 1997 (that is, before the onset of the financial crash). The Scottish price level, reflected in the consumer price index (CPI), falls by 1.43% in the short run and by 3.21% over the long run.

This reduction in price stimulates Scottish exports to both the RUK and the ROW which increase by around 3% in the short run and just below 8% in the long run. In the short run, imports from the RUK and the ROW are both higher than their base-year values by 0.66% and 0.31% respectively. This reflects the increase in Scottish GDP and the short-run capacity constraints. However, in the long run RUK imports to Scotland are only 0.07% above, and the ROW imports have fallen below their base-year values as a result of import substitution. The stimulus to Scottish exports generates associated positive impacts on consumption, investment and intermediate demand. However, the expansion in population, through inter-regional migration, slows the growth in GDP per capita. This peaks in period 5 at a value of 4.41%, but its long-run increase is 4.17%, with a long-run rise in GDP per employee of 4.05%.

There is a positive and continuing impact on output for all Scottish production sectors, with long-run increases lying between 5.67% in ‘Other services’ and 9.22% in ‘Quarrying, construction and water supply’. The long-run output change depends partly on a sector’s exposure to the efficiency improvement through its labour intensity, but is also strongly affected by the sector’s export intensity and the strength of local demand effects. ‘Other services’ sells primarily to domestic consumption, which increases by a relatively small amount. However, ‘Quarrying, construction and water supply’ are more closely linked to investment demand domestically and also include exports to the off-shore oil sector.

Impacts in the neighbouring region (RUK)

The non-treated neighbouring region, the RUK, is affected by spread and backwash effects through trade and labour migration links. The results are shown in the fourth to sixth columns in Table 2. It is important to stress the relevance of these results to the regional setting, particularly from the Scottish perspective. Scottish trade is dominated by trade with the RUK. For 2004, 69% of Scottish imports are recorded as coming from, and 63% of exports as going to, the RUK. The impact on the RUK economy is a combination of four effects. First, aggregate output and income is rising in Scotland, an important export market for RUK products. Second, the reduction in the price of Scottish imports increases the competitiveness of RUK commodities in ROW markets by lowering the price of intermediate inputs and the nominal wage. Third, despite the reduction in RUK prices, RUK products lose competitiveness relative to Scottish commodities and this adversely affects exports to Scotland. Finally, the Scottish real wage will initially rise, and the unemployment rate fall, relative to the RUK value. As was observed in the fifth section, this leads to the emigration from the RUK to Scotland, which increases the RUK real wage and thereby puts downward pressure on RUK competitiveness. The overall impact in the RUK depends on the relative strength of these four effects.

Whilst in the short run both total UK employment and GDP increase (by 0.02%), in the long run they both fall: GDP by 0.20% and employment by 0.25%. RUK GDP falls in all periods after period 1, with its value lower than the initial base-year level by period 6, and the RUK population falls, through emigration, from the start. Moreover, population declines more rapid than GDP. This implies that even though RUK GDP is falling, GDP per head is rising monotonically in this simulation. In the long run, population falls by 0.33% so that GDP per head has risen by 0.13%. This increase is much smaller than the corresponding increase in Scotland but again it is supported by an endogenous increase in capital intensity, with investment falling by less than employment.

Table 2 reveals an initial increase in RUK exports to the ROW and Scotland of 0.20% and 0.66% respectively, whilst RUK imports from the ROW fall by 0.19% and from Scotland rise by 3.02%. In the long run, RUK CPI continues to fall by 0.22% against the 3.21% CPI decline in Scotland. In this time period, RUK exports to the ROW are therefore further increased, and imports reduced by 0.36%, and 0.61% respectively. However, in RUK trade with Scotland, in the long run exports rise by only 0.07% whilst RUK imports increase by 7.85%.

The long-run net-negative trade stimulus produces the fall in RUK economic activity and this is accompanied by a contraction in other macroeconomic variables: household consumption, investment and employment decline by 0.27%, 0.17% and 0.25% respectively. However, the UK overall labour supply constraint is evident through an increased real wage rate and a reduced unemployment rate that reflects the 0.33% decrease in RUK population over the long run.

In the RUK, outputs in all industries increase in the short run, but over time they fall to below their initial levels. The production in those sectors most closely linked to domestic consumption, that is ‘Retail, distribution and transport’ and ‘Other services’, begins to decline first and their long-run reduction is the greatest. This mirrors the long-run 0.27% decline in RUK household consumption.

For the RUK economy, the impact of the increase in labour productivity in Scotland is ambivalent. In terms of the aggregate economic activity, there are negative backwash effects: total GDP and employment both fall. However, when measured by changes in productivity per head and real wage, the impact is positive.

CO_2 SIMULATION RESULTS

This study is particularly interested in the changes in CO_2 emissions that accompany the improvements in Scottish labour efficiency. As measured by GDP per head, there is economic growth in both Scotland and the RUK. This research tests the environmental EKC conjecture that such growth can be accompanied by reductions in per capita CO_2 levels.

The CO_2 simulation results for Scotland

Under the PAP accounting measure, Scottish CO_2 emissions rise steadily from the outset: in the short run there is a 2.5% increase over the base period value and in the long run this reaches just less than 7%. In each Scottish production sector the use of all inputs increases, as does the associated CO_2 generation. Direct emissions in the household sector also rise. However, this growth in PAP emissions is dominated by the expansion in the highly carbon-intensive ‘Energy’ sector, accounting here for almost half the long-run increase in PAP emissions.

Comparing the Scottish GDP and PAP CO_2 figures, from the initiation of the productivity shock Scottish GDP grows faster than CO_2 generation, but the difference is small. Although there will be some substitution of value added for intermediate inputs in production, and direct CO_2 emissions from consumption are growing at a relatively low rate, the growth in the CO_2-intensive energy sector is more rapid than the overall growth in GDP. This means that the CO_2 intensity of Scottish GDP falls below its base-year value by a modest 0.75% in the long run. This is not enough to offset the corresponding increase

Table 3. Long-run change (tonnes) in CO_2 embodied in imports from the rest of the world (ROW) to the UK regional and national economies in response to the increase in Scottish labour productivity.

	Scotland	RUK	UK
CO_2 embodied in imports from the ROW (tonnes)	144,715	−1,041,055	−896,340
CO_2 embodied in imports of commodities			
Energy	205,485	−504,848	−299,362
Extraction, quarrying, construction and water supply	11,333	−42,763	−31,430
Agriculture and fishing	4231	−30,749	−26,517
Manufacturing	−21,799	−250,721	−272,520
Retail, distribution and transport	−50,035	−192,139	−242,174
Other services	−7894	−19,835	−27,729

in GDP per head, so that long-run Scottish per capita CO_2 emissions, as given by the PAP measure, increase by 3.25%.

Whilst Scottish total CAP emissions rise by 1.44% in the short run and 3.13% in the long run, these are significantly smaller than the corresponding increases in GDP. Table 2 indicates that the long-run Scottish CAP CO_2 intensity of GDP falls by over 4.30% below its base-year value. This is greater than the 4.17% increase in GDP per head, so that per capita CAP CO_2 emissions also fall. There is decoupling in the long run.

The short-run increase in Scottish CAP CO_2 emissions is inflated by the initial increase in imports from the ROW, which tend to be more CO_2-intensive than the average unit of consumption of UK (Scottish and RUK) goods and services. This is due to the commodity composition of imports and associated external polluting technologies.[11] Moreover, there is a further net change in the composition of imports from the ROW as individual activities grow at different rates. This is reflected in the results in Table 3.

There is a fall in the long-run ROW imports to Scotland, compared with their base-year levels. Nevertheless, there is a net increase of 0.8% or 144.7 kilotonnes tonnes in CO_2 embodied in ROW imports to Scotland over this period caused by the change in their sectoral composition. Whilst imports are falling for 'Manufacturing', 'Retail distribution and transport' and 'Other service', they are rising in the other three sectors and in particular in the CO_2-intensive 'Energy' sector. According to the data supplied by the OECD, non-European Union countries such as Russia and Canada are important in terms of Scottish 'Energy' imports.

The CO_2 simulation results for RUK

In this case, after an initial rise in total RUK emissions for both PAP and CAP measures, there is a subsequent fall after period 5. But whilst for the PAP measure the long-run total CO_2 emissions fall 0.02% below the original base-year value, using the CAP method emissions actually rise by 0.04%. The long-run fall in RUK GDP is more rapid than the declines in either the CAP or the PAP emissions measures, implying that RUK GDP emissions' intensities rise over time and reinforce, rather than offset, the increase in GDP per head. For the RUK, CO_2 emissions per head rise more rapidly than GDP per head. Therefore, the EKC conjecture emphatically fails in the RUK simulations.

The growth in RUK measured productivity and the real wage is driven by a combination of demand and supply effects, but there is no change in the underlying RUK efficiency. The aggregate macro-economic variables and the changes in the PAP and CAP measures of emissions would therefore be expected to move more closely in line with one another than in the case of Scotland. Also, one reason for the higher emissions measured using the CAP method is that public expenditure is held constant in these simulations, so that although the simulated RUK population, private consumption and GDP are falling, public consumption remains unchanged.

Finally, this section considers the change in the relationship between the economies of the RUK and the ROW. Note from Table 3 that the 0.61% drop in imports from the ROW reported in Table 2 is accompanied by reductions in CO_2 embodied in imports from the ROW to the RUK. This applies to commodities from each ROW sector. Therefore, despite the slight positive effect on total RUK CAP CO_2 emissions, underlying carbon leakage falls. Moreover, the reduction in carbon embodied in RUK imports from the ROW is sufficiently large to offset the increases associated with Scottish imports from the ROW in sectors 1–3.

This means that there is a net reduction of 896.3 kilotonnes across all commodities imported into the UK economy as a whole, as reported in the third column of Table 3. Thus, the increase in labour efficiency in the Scottish regional economy leads to negative carbon leakage at the UK level, but an increase in PAP emissions of just over 3.5 million tonnes. This is largely driven by increased export demand from the ROW in both regions (particularly Scotland) as competitiveness improves. Therefore, rather than there being carbon leakage associated with economic growth, there is something of a 'carbon blow-back'.

SENSITIVITY

All scenarios were also run with no migration, in which inter-regional impacts are therefore only transmitted through goods and services trade flows. This causes a more limited expansion in Scotland, because of the fixed labour force without migration. Despite a long-run 0.17% increase in aggregate Scottish consumption, there is a net decrease in CAP due to substitution in favour of Scottish outputs against the more emissions-intensive imports from the ROW. The RUK also enjoys a small expansion due to the indirect demand shock with no additional supply constraint from out-migration. The 0.01% increase in RUK consumption is also accompanied by a net reduction in CAP due to a fall in ROW imports and substitution in favour of Scottish-produced commodities.

Sensitivity analysis has also been conducted with respect to the key parameter values.[12] The elasticities of substitution in production govern the extent of substitution towards more efficient labour and away from polluting input use (where emissions are linked, as appropriate, to use of energy inputs). The core insight is that for Scotland, the more (less) substitution in favour of labour is allowed, the more (less) the increase in GDP outstrips CO_2 emissions. However, where migration is possible, more labour is drawn away from the RUK, so that GDP falls faster than CO_2 in that region. The greatest GDP growth at a national level is found, the weaker the substitution effect in favour of labour in Scotland, but with the greatest increase in the PAP CO_2 measure. Given the importance of interregional migration in many subnational regional economies, this result provides generic insight.

However, it is important to note that these findings are predicated on the fact that Scotland starts out from a position of being less labour and emissions efficient than the RUK. Had the labour efficiency improvement occurred in the RUK, the impacts at national level would be more positive, the easier it is to substitute in favour of labour in that region and to attract labour in from other, less productive, regions. While the authors have not conducted sensitivity analysis with respect to trade elasticities, the same basic argument will follow. Anything that facilitates a fuller expansionary response (i.e., a greater response of exports to the ROW to falling Scottish prices) will lead to more positive economic impacts, accompanied by increased PAP emissions but a decreased reliance on imports, and emissions embedded therein, in the region where productivity improves. However, the economic and environmental impacts in other regions and at the national level will depend on whether labour moves to/from regions that are more/less productive in terms of the labour and emissions intensity of production.

DISCUSSION AND CONCLUSIONS

This paper considers the economic and environmental interaction between two regions, Scotland and the RUK, generated by efficiency-driven growth in one. In the simulation results, the increased labour productivity in Scotland generates a supply-driven export-led expansion in that region, but also an indirect demand boost that initially stimulates aggregate economic activity in the RUK. However, there is a gradually increasing negative supply shock to the RUK as a result of inter-regional migration to Scotland. Although this eventually leads to a fall in RUK GDP and employment, the subsequent reduced labour supply produces higher RUK real wages and GDP per head.

In Scotland, where the labour efficiency shock occurs, there is growth in absolute pollution levels using both production and consumption accounting methods. In the RUK there is a slight fall in the long-run absolute level of PAP emissions, but an increase in CAP emissions. Given the fall in RUK economic activity, the most straightforward way to operationalize the environmental EKC is to look at the relationship between emissions and GDP both measured per head. In the case of Scotland, there is support for the EKC conjecture where CO_2 emissions are measured using the CAP method. Essentially, consumption per head is rising by much less than GDP per head, plus there is substitution of imports from the ROW by Scottish-produced goods and services, which are typically less energy intensive than their ROW counterparts. However, for the RUK economy, proportionate GDP and consumption change are much closer and there is a lower proportionate substitution away from ROW imports because the competitiveness effects are less strong.

The simulation results point to key differences between regional economic and environmental change powered primarily by direct efficiency improvements and those determined by secondary adjustments to price, output and income changes occurring elsewhere. However, there are a number of issues that need to be borne in mind when interpreting these results and which will serve as useful guides for future research.

First, for the type of growth simulated here, there is no strong evidence for the EKC conjecture. But note that there were assumed to be no changes in tastes as incomes change, no policies implemented specifically to limit climate change, and the efficiency improvement was directed towards greater efficiency in the use of labour, not intermediate inputs in general or energy in particular

Second, the focus has been specifically on economic and environmental spillovers between two regions of the UK. The ROW economy has not been explicitly modelled. Nevertheless, there is some evidence from the CO_2 embedded in ROW imports to the UK that the Scottish efficiency improvement might have a benign effect on CO_2 generation in the ROW. Also, the assumption has been made that whilst inter-regional migration is possible, the UK national population is fixed. However, international, and especially intra-European Union, migration is an increasingly important phenomenon that should be examined.

Finally, an equilibrating view of the operation of migration in multi-regional systems has been adopted. Whilst there is econometric support for this approach, it is possible to take a much less benign viewpoint that stresses the selective nature of inter-regional migration. The potential accompanying adverse impacts on entrepreneurship, dependency levels and the skill base could result in a reduction in per capita GDP of the local economy that is losing population.

ACKNOWLEDGEMENTS

The authors are grateful for the input and advice of the input–output team at the Office of the Chief Economic Advisor at the Scottish government as well as Tommy Wiedmann, formerly of the Stockholm Environment Institute, in constructing UK input–output and regional and national imports data; and to Nori Yamano, at the Organisation for Economic Co-operation and Development (OECD), who worked with the authors to identify the pollution content of UK imports. The authors are also grateful to Soo Jung Ha, Janine De Fence and Stuart McIntyre for research assistance. The paper was much improved by valuable comments made on earlier versions by the editor and two anonymous referees.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

FUNDING

The research reported in this paper was supported by the UK Economic and Social Research Council (ESRC) [reference number RES-066-27-0029] and the Scottish government's ClimateXChange project.

ORCiD

Peter McGregor http://orcid.org/0000-0003-1221-7963

NOTES

1. The paper focuses on both domestic carbon dioxide (CO_2) emissions and emissions embodied in imports to support domestic consumption. In 2011, CO_2 emissions accounted for around 77% of Scottish GHG emissions.
2. Other factors likely to play a part in any EKC relationship include endogenous changes in consumers' tastes and the willingness by consumers and voters to pay for green products or impose pollution controls. The European Environment Agency (2015) provides a rich source of detail on the actual change in GHG emissions amongst European nations.
3. The interregional SAM uses 2004 input–output data for Scotland published by the Scottish government (see http://www.scotland.gov.uk/Topics/Statistics/Browse/Economy/Input-Output) and UK analytical IO tables (see http://www.strath.ac.uk/fraser/research/2004ukindustry-byindustryanalyticalinput-outputtables/) derived from the UK Supply and Use tables produced by the Office for National Statistics (ONS) (see http://www.statistics.gov.uk/STATBASE/Product.asp?vlnk=3026). Interregional trade data, unpublished at the time, were provided by the Scottish government as were Scottish environmental accounting data. The UK environmental accounts may also be accessed at the ONS (see http://www.statistics.gov.uk/about/methodology_by_theme/Environmental_Accounts/default.asp).
4. The reliability of the available Scottish environmental accounting data limits the sectoral breakdown. Results from allocating emissions across the 128 sectors of the Scottish input–output tables are inexplicably out of line with UK sectoral estimates. The Scottish government is therefore concerned about their reliability, though these data have now been released for public scrutiny (see http://www.scotland.gov.uk/Topics/Statistics/Browse/Economy/SNAP/expstats/EnvironmentalAccounts).
5. In a working version of this paper this assumption is relaxed (see pp. 20–22 of the document at: https://www.stir.ac.uk/media/schools/management/documents/workingpapers/SEDP-2011-13-Turner-Hanley-Cui.pdf/).
6. See section 4.2 of the document at: http://www.strath.ac.uk/media/departments/economics/researchdiscussionpapers/2009/09-15KT.pdf/.
7. Atkinson, Hamilton, Ruta, and Van der Mensbrugghe (2010) and Distefano, Riccaboni, and Marin (2014) offer alternative approaches to the calculation of CAP measures using input–output methods.
8. The Scottish government has a target to reach the top quartile of the OECD productivity rankings by 2017. This seems overoptimistic, so that a more realistic comparison of parity with the rest of the UK, which is often implicitly used as a benchmark by the Scottish government, is adopted here.
9. The model is parameterized on, and the adjustment rates informed by, econometric work using annual data.
10. A more detailed analytical treatment of an increase in labour efficiency in a single region context is given in Hermannsson, Lecca, and Swales (2014).
11. The CO_2 embodied in imports reflects only the direct CO_2 generated in their production. More sophisticated methods are available but typically involve global input–output modelling (Atkinson et al., 2010). The OECD was involved in the construction of the World Input–Output database (WOID) data (Timmer et al., 2015), but has subsequently extended this to develop its own inter-country input–output database which is in an ongoing state of evolution and can be accessed at: http://www.oecd.org/trade/input-outputtables.htm/.
12. See sections 4.2–4.3 of the document at: https://www.strath.ac.uk/media/departments/economics/researchdiscussionpapers/2009/09-15KT.pdf/.

REFERENCES

Armington, P. (1969). A theory of demand for products distinguished by place of production. *IMF Staff Papers*, *16*, 157–178.
Arrow, K., Bolin, B., Costanza, R., Dasgupta, P., Folke, C., Holling, C., … Perrings, C. (1995). Economic growth, carrying capacity,

and the environment. *Science*, *268*, 520–521. doi:10.1126/science.268.5210.520

Atkinson, G., Hamilton, K., Ruta, G., & Van der Mensbrugghe, D. (2010). *Trade in 'virtual carbon': Empirical results and implications for policy* (World Bank Policy Research Working Paper Series, 5194). Washington, DC: World Bank.

Babiker, M. H. (2005). Climate change policy, market structure and carbon leakage. *Journal of International Economics*, *65*, 421–445. doi:10.1016/j.jinteco.2004.01.003

Bergman, L. (2005). CGE modelling of environmental policy and resource management. In K. G. Mäler, & J. Vincent (Eds.), *Handbook of environmental economics: Economy wide and international environmental issues* (pp. 1273–1306). Amsterdam: North-Holland/Elsevier.

Bruvoll, A., & Faehn, T. (2006). Transboundary effects of environmental policy: Markets and emission leakages. *Ecological Economics*, *59*, 499–510.

Climate Change (Scotland) Act. (2009). Edinburgh: The Stationery Office (TSO).

Costantini, V., Mazzanti, M., & Montini, A. (2013). Environmental performance, innovation and spillovers. Evidence from a regional NAMEA. *Ecological Economics*, *89*, 101–114. doi:10.1016/j.ecolecon.2013.01.026

Department for Environment, Food and Rural Affairs (DEFRA). (2012). *Statistical release: UK's carbon footprint 1990–2009*. Retrieved from http://www.defra.gov.uk/statistics/files/Release_carbon_footprint_08Mar12.pdf.

Distefano, T., Riccaboni, M., & Marin, G. (2014). *Global virtual water trade: Integrating structural decomposition analysis with network theory* (Working Papers No. 8/2014, revd August). Lucca: IMT Institute for Advanced Studies.

Elliot, J., Kortum, S., Munson, T., Pérez, F., & Weisbach, D. (2010). Trade and carbon taxes. *American Economic Review: Papers and Proceedings*, *100*, 465–469. doi:10.1257/aer.100.2.465

European Environment Agency. (2015). *Why did greenhouse gas emissions decrease in the EU between 1990 and 2012?* Copenhagen: European Environment Agency.

Faehn, T., & Bruvoll, A. (2009). Richer and cleaner – At others' expense? *Resource and Energy Economics*, *31*, 103–122. doi:10.1016/j.reseneeco.2008.11.001

Galvez, J. V. (2014). Estimating a wage curve for the United Kingdom (MSc dissertation), University of Edinburgh, Edinburgh.

Gerlagh, R., & Kuik, O. (2014). Spill or leak? Carbon leakage with international technology spillovers: A CGE analysis. *Energy Economics*, *45*, 381–388. doi:10.1016/j.eneco.2014.07.017

Gibson, H. (1990). *Export competitiveness and UK sales of Scottish manufacturers*. Paper presented at the Scottish Economists Conference, The Burn, UK.

Greenaway, D., Leyborne, S., Reed, G., & Whalley, J. (1993). *Applied general equilibrium modelling: Applications, limitations and future developments*. London: HMSO.

Harrigan, F., McGregor, P. G., Perman, R., Swales, J. K., & Yin, Y. P. (1991). AMOS: A macro–micro model of Scotland. *Economic Modelling*, *8*, 424–479. doi:10.1016/0264-9993(91)90028-M

Harris, J., & Todaro, M. (1970). Migration, unemployment and development: A two sector analysis. *American Economic Review*, *60*, 126–142.

Harris, R. (1989). *The growth and structure of the UK regional economy, 1963–85*. Aldershot: Avebury.

Hermannsson, K., Lecca, P., & Swales, K. (2014). *How much does a single graduation cohort from further education colleges contribute to an open regional economy?* Strathclyde Economics Discussion Paper Series No. 14-04. Glasgow; University of Strathclyde.

House of Commons Energy and Climate Change Committee. (2012). *Consumption-based emissions reporting* (Twelfth Report of Sessions 2010–12, Volume 1. HC 1646. Published 18 April 2012 by authority of the House of Commons). London: The Stationary Office (TSO). Retrieved from http://www.parliament.uk/eccpublications

Jaffe, A., Newell, R., & Stavins, R. (2003). Technological change and the environment. In K.-G. Mäler, & J. R. Vincent (Eds.), *Handbook of environmental economics, Vol. 1* (pp. 461–516). Amsterdam: North-Holland/Elsevier.

Layard, R., Nickell, S., & Jackman, R. (1991). *Unemployment: Macroeconomic performance and the labor market*. New York: Oxford University Press.

Levinson, A. (2009). Technology, international trade, and pollution from US manufacturing. *American Economic Review*, *99*, 2177–2192. doi:10.1257/aer.99.5.2177

Marin, G., & Mazzanti, M. (2013). The evolution of environmental and labor productivity dynamics. *Journal of Evolutionary Economics*, *23*, 357–399. doi:10.1007/s00191-010-0199-8

Marin, G., Mazzanti, M., & Montini, A. (2012). Linking NAMEA and input output for 'consumption vs. production perspective' analyses. *Ecological Economics*, *74*, 71–84. doi:10.1016/j.ecolecon.2011.11.005

Mazzanti, M., & Montini, A. (2010). Embedding the drivers of emission efficiency at regional level – Analyses of NAMEA data. *Ecological Economics*, *69*, 2457–2467. doi:10.1016/j.ecolecon.2010.07.021

Mazzanti, M., & Zoboli, R. (2009). Environmental efficiency and labour productivity: Trade-off or joint dynamics? A theoretical investigation and empirical evidence from Italy using NAMEA. *Ecological Economics*, *68*, 1182–1194. doi:10.1016/j.ecolecon.2008.08.009

Miller, R. E., & Blair, P. D. (2009). *Input–output analysis: Foundations and extensions*. Cambridge: Cambridge University Press.

Musolesi, A., & Mazzanti, M. (2014). Nonlinearity, heterogeneity and unobserved effects in the carbon dioxide emissions–economic development relation for advanced countries. *Studies in Nonlinear Dynamics & Econometrics*, *18*, 521–541.

Office for National Statistics (ONS). (2014). *Regional economic indicators, July 2014*. Retrieved from http://www.ons.gov.uk/ons/rel/regional-trends/regional-economic-indicators/july-2014/rep-regional-economic-indicators.html

Partridge, M., & Rickman, D. (2010). Computable general equilibrium (CGE) modelling for regional economic development analysis. *Regional Studies*, *44*, 1311–1328. doi:10.1080/00343400701654236

Scottish Government. (2011). *Low carbon Scotland: Meeting the emissions reduction targets 2011–2022*. Edinburgh: Scottish Government. Retrieved from http://www.scotland.gov.uk/Resource/Doc/346760/0115345.pdf

Scottish Government. (2015). *Scotland performs*. Edinburgh: Scottish Government. Retrieved from http://www.gov.scot/About/Performance/scotPerforms/purpose s/productivity

Sheldon, I. (2006). Trade and environmental policy: A race to the bottom? *Journal of Agricultural Economics*, *57*, 365–392. doi:10.1111/j.1477-9552.2006.00056.x

Timmer, M. P., Dietzenbacher, E., Los, B., Stehrer, R., & De Vries, G. J. (2015). An illustrated user guide to the World Input–Output Database: The case of global automotive production. *Review of International Economics*, *23*, 575–605. doi:10.1111/roie.12178

Turner, K., Gilmartin, M., McGregor, P. G., & Swales, J. K. (2012). An integrated IO and CGE approach to analysing changes in environmental trade balances. *Papers in Regional Science*, *91*, 161–180. doi:10.1111/j.1435-5957.2011.00365.x

Turner, K., & Hanley, N. (2011). Energy efficiency, rebound effects and the environmental Kuznets curve. *Energy Economics*, *33*, 709–720. doi:10.1016/j.eneco.2010.12.002

Turner, K., Lenzen, M., Wiedmann, T., & Barrett, J. (2007). Examining the global environmental impact of regional consumption activities – Part 1: A technical note on combining input–output and ecological footprint analysis. *Ecological Economics*, *62*, 37–44. doi:10.1016/j.ecolecon.2006.12.002

Turner, K., Yamano, N., Druckman, A., Ha, S. J., De Fence, J., McIntyre, S., & Munday, M. (2011). *An input–output carbon accounting tool with carbon footprints estimates for the UK and Scotland* (Economic Commentary, Special Edn, January, 6–20). Glasgow: Fraser of Allander Institute.

Vollebergh, H. R. J., Melenberg, B., & Dijkgraaf, E. (2009). Identifying reduced-form relations with panel data: The case of pollution and income. *Journal of Environmental Economics and Management*, *58*, 27–42. doi:10.1016/j.jeem.2008.12.005

Wiedmann, T. (2009). A review of recent multi-region input–output models used for consumption-based emission and resource accounting. *Ecological Economics*, *69*, 211–222. doi:10.1016/j.ecolecon.2009.08.026

York, R., Rosa, E. A., & Dietz, T. (2003). STIRPAT, IPAT and ImPACT: Analytic tools for unpacking the driving forces of environmental impacts. *Ecological Economics*, *46*, 351–365. doi:10.1016/S0921-8009(03)00188-5